PB-224 862

# NAS REPORT ON TECHNOLOGICAL FEASIBILITY OF 1975-76 MOTOR VEHICLE EMISSION STANDARDS

## AUTOMOTIVE SPARK IGNITION ENGINE EMISSION CONTROL SYSTEMS TO MEET THE REQUIREMENTS OF THE 1970 CLEAN AIR AMENDMENTS

NATIONAL ACADEMY OF SCIENCES

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

MAY 1973

Distributed By:
NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

**BIBLIOGRAPHIC DATA SHEET**

1. Report No.

2.

PB 224 862

4. Title and Subtitle

Automotive Spark Ignition Engine Emission Control Systems to Meet the Requirements of the 1970 Clean Air Amendments, National Academy of Sciences

5. Report Date
May 1973

6.

7. Author(s)
Committee on Motor Vehicle Emissions - CMVE/NAS

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Committee on Motor Vehicle Emissions
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

10. Project/Task/Work Unit No.

11. Contract/Grant No.
68-01-0402

12. Sponsoring Organization Name and Address

Environmental Protection Agency
Office of Air and Water Programs - Mobile Source Air Pol. Control.
401 M Street SW Room 1219 East Tower
Washington, D.C. 20460

13. Type of Report & Period Covered
Panel Report

14.

15. Supplementary Notes
Committee Report supported by seven (7) panel reports also available from NTIS

16. Abstracts

This report summarizes the data available on the performance of emission control systems for spark-ignition engines that approach the degree of control required to meet the 1975 and 1976 automobile emission standards as required by the 1970 Clean Air Amendments. Emission control for conventional engines and also unconventional approaches for spark-ignition engines are discussed. The lead time necessary for production is also discussed.

17. Key Words and Document Analysis. 17a. Descriptors

air pollution
motor vehicles
emissions
control technology
catalysts

17b. Identifiers/Open-Ended Terms

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

17c. COSATI Field/Group

18. Availability Statement
Release unlimited

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page
UNCLASSIFIED

21. No. of Pages
115

22. Price
$4.25

1a

# AUTOMOTIVE SPARK IGNITION ENGINE EMISSION CONTROL SYSTEMS TO MEET THE REQUIREMENTS OF THE 1970 CLEAN AIR AMENDMENTS

Report of the

Emission Control Systems Panel

to the

COMMITTEE ON MOTOR VEHICLE EMISSIONS

NATIONAL ACADEMY OF SCIENCES

May 1973

## NOTICE

The Committee on Motor Vehicle Emissions has evaluated the technological feasibility of meeting the light-duty motor vehicle emissions standards as prescribed by the Clean Air Amendments of 1970. This study was performed under the sponsorship of the National Academy of Sciences and with the express approval of the Governing Board of the National Research Council.

The Committee obtained much of its information from eight panels of consultants, each panel dealing with a particular subject area of importance in the Committee deliberations. Panel members were selected by the Committee on the basis of recognized competence in specific areas.

The panel reports are reports of the panels to the Committee. Before publication, each panel report was reviewed by appointed members of the Committee. The views represented by the panels are one of the sources of information provided to the Committee and were used as a partial basis for the Committee judgments.

# PREFACE

In legislating the Clean Air Amendments of 1970, the Congress asked the Environmental Protection Agency to contract with the National Academy of Sciences to conduct a comprehensive study and investigation of the technological feasibility of meeting the motor vehicle emissions standards prescribed in accordance with the law. In responding to this request, pursuant to a contract with the Environmental Protection Agency, the Academy established a Committee on Motor Vehicle Emissions and charged it with the conduct of this study. The Committee published the results of its work in a report to the Environmental Protection Agency dated February 12, 1973.

As means of providing itself with authoritative information and expertise in the various critical aspects of the problem it undertook to study, the Committee appointed specialist panels to undertake investigations and report their findings. The following report, Automotive Spark Ignition Engine Emission Control Systems to Meet the Requirements of the 1970 Clean Air Amendments, presents the findings of one of those panels.

Taken together, the special panel reports constitute a very substantial accumulation of data and analysis brought together by many specialsits in many investigations in a very fast-moving area of technological development. In its published report, the Committee on Motor Vehicle Emissions has, of course, brought together that part of all this information and analysis required to fulfill its stated obligation to the Environmental Protection Agency. The separate reports of the specialist panels are published for the public record and to complete the documentary record.

An early draft of this report was available to the CMVE and was used by the Committee in formulating its own report. Since then, some later data have been received, and some of these data are included in this report.

## EMISSION CONTROL SYSTEM PANEL MEMBERS

John B. Heywood, Department of Mechanical Engineering,
Massachusetts Institute of Technology
Panel Chairman

Jay A. Bolt, Department of Mechanical Engineering,
University of Michigan

Ernest M. Jost, Materials and Electronic Controls Group,
Texas Instruments, Inc.

Henry K. Newhall, Fuels Division, Chevron Research Company

William A. Sirignano, Department of Aerospace and Mechanical
Sciences, Princeton University

David E. Wulfhorst, Cummins Engine Company, Inc.

## PERFORMANCE PANEL MEMBER

King D. Bird, Vehicle Research Department, Calspan Corporation

## Table of Contents

1. Summary and Evaluation . . . . . . . . . . . . . . . 1
2. Scope of Panel's Study . . . . . . . . . . . . . . . 5
3. Background . . . . . . . . . . . . . . . . . . . . 7

4. Emission Control Technology

Exhaust Emission Controls . . . . . . . . . . . . . 17
Reducing Catalytic Converter for $NO_x$ . . . . . . . . . 17
Secondary Air System . . . . . . . . . . . . . . . 18
Thermal Reactor. . . . . . . . . . . . . . . . . . 18
Oxidizing Catalytic Converter . . . . . . . . . . . 18
Three-Way Catalytic Converter . . . . . . . . . . . 19
Carburetion. . . . . . . . . . . . . . . . . . . . 19
Cold-Start Emission Controls . . . . . . . . . . . 21
Dual Fuel Cars . . . . . . . . . . . . . . . . . . 23
Supplemental Heat for the Catalyst . . . . . . . . 23
Cold Storage Controls . . . . . . . . . . . . . . . 23
Modification of Fuels . . . . . . . . . . . . . . . 24
Electronic Fuel Injection . . . . . . . . . . . . . 25
Feedback Systems for Air-Fuel Ratio Control. . . . . . 27
Exhaust Gas Recycle (EGR) . . . . . . . . . . . . . 30
Potential for Engine Emissions Reduction . . . . . . 32

5. Status of 1975 Conventional Engine Emission Control Systems. 36

6. Status of 1976 Conventional Engine Emission Control Systems. 40

Dual-Catalyst Systems . . . . . . . . . . . . . . . 40
Richer Carburetor Setting . . . . . . . . . . . . . 40
Increased EGR . . . . . . . . . . . . . . . . . . . 40
Air Injection Controls . . . . . . . . . . . . . . . 42
Three-Way Catalyst System . . . . . . . . . . . . . 54
Systems with Thermal Reactors . . . . . . . . . . . 55

7. Wankel Rotating Combustion Engines . . . . . . . . . 64

8. Stratified-Charge and Dilute-Combustion Engines . . . . 74
Open-Chamber Stratified Charge Engines . . . . . . . . 75
Divided Combustion Chamber Engines: Fuel Injected . . . 81
The Honda Compound Vortex Controlled Combustion (CVCC) Engine . . . . . . . . . . . . . . 84
Dilute Combustion Engines . . . . . . . . . . 88
9. Vehicle Performance, Driveability and Fuel Economy . . . . 93
10. Averaging of Emissions . . . . . . . . . . . . . 99

## APPENDIXES

A. Organizations Consulted by the Panel . . . . . . . 102
B. Questionnaires . . . . . . . . . . . . . 103

## TABLES

1 Federal Emission Control Requirements for Light-Duty Vehicles. . . . . . . . . . . . . . 8
2 Federal Exhaust Emission Standards in Table 1 Converted to 1975-76 CVS-CH Test Procedure. . . . . . . 10
3 Engine Emissions at Low Mileage: Mean and Standard Deviation . . . . . . . . . . . . . . 33
4 Deterioration in Engine Emissions over 50,000 miles. . . 35
5 Emissions Performance of Major Manufacturers 1975 Model-Year Development Fleets . . . . . . . . 39
6 Effect of Catalyst Material on Operating Temperature and Ammonia Production . . . . . . . . . . 44
7 Examples of Best Low Mileage Emissions Measurements with Dual-Catalyst Systems on Experimental 1976 Vehicles. . . . . . . . . . . . . . 46

8. Emissions As Function of Mileage for Durability Tests on Dual-Catalyst Systems . . . . . . . . . 49

9. Low-Mileage Emissions from Compact and European Vehicles Equipped with Three-Way Catalyst Systems . . . . 56

10. Low-Mileage Emissions of Thermal Reactor Systems . . . 59

11. Durability Data for Thermal Reactor Systems . . . . 61

12. Emissions Data for Reactor-Converter Systems . . . . 62

13. Best Emission Results, Thermal Reactor and Wankel Engine 2750-lb Compact Car. . . . . . . . 68

14. Effect of EGR on Wankel Bare Engine $NO_x$ Emissions. . . 69

15. Emissions at Low Mileage, Rotary Engine with Oxidation Catalysts . . . . . . . . . . 72

16. Emissions from Military Jeep with Stratified-Charge Engine. . . . . . . . . . . . . . 78

17. Low-Mileage Emission Levels for PROCO Conversion . . . 79

18. Single-Cylinder Engine Performance and Emissions . . . 83

19. Low-Mileage Emissions Data from Honda Tests of 1975 CVCC Systems . . . . . . . . . . . 87

20. Durability Data from Honda Tests of 1975 CVCC Systems. . 89

21. Low-Mileage Emission Data from CVCC System Developed for Low $NO_x$ . . . . . . . . . . . . . 90

22. Low-Mileage Emissions: Ford Fast-Burn Engine . . . 92

23. Low-Mileage Emission Targets for Different Fraction of Production Cars Meeting Standards. . . 100

## FIGURES

1. Federal exhaust emission standards in terms of 1975-76 CVS-CH test procedure . . . . . . . . . . 11

2. Emissions during the first 7.5 miles of the CVS test, showing importance of HC during cold start. . . . 22

3 Emissions during the first 7.5 miles of the CVS test, showing importance of CO during cold start . . . . 22

4 $NO_x$ Emissions versus Fuel Economy. . . . . . . . 31

5 Schematic of GM 1975 system . . . . . . . . 37

6 Schematic of GM 1976 dual-catalyst system. . . . . . 41

7 Effect of air-fuel ratio on $NO_x$ emissions for a Wankel and a conventional spark-ignition engine at constant loads . . . . . . . . . . 66

8 Fuel economy loss at various $NO_x$ levels for a range of EGR percentages and air-fuel ratios for a Toyo Kogyo Wankel engine . . . . . . . 71

9 Stratified-charge internal-combustion engine (PROCO) . . 76

10 CVCC engine . . . . . . . . . . . . 85

## 1. Summary and Evaluation

This report summarizes the data available on the performance of emission control systems for spark-ignition engines that approach the degree of control required to meet the 1975 and 1976 automobile emission standards as required by the 1970 Clean Air Amendments.* Emission controls for conventional engines and also several unconventional approaches for spark-ignition engines are discussed. The lead times required to develop and manufacture new types of spark-ignition engines in several engine sizes for different types of vehicles are so long that, in the Panel's judgment, the bulk of 1975 and 1976 model-year production must be conventional reciprocating carbureted spark-ignition engines of the type already in large-scale mass production. However, new types of engines, such as stratified charge or Wankel engines, are expected to be in mass production by a few manufacturers by 1975 and 1976 model years. The characteristics of these alternative spark-ignition engines are therefore important in the longer term.

The automobile manufacturers are now testing fleets of experimental vehicles for the 1975 model year. For most manufacturers, these fleet vehicles use conventional carbureted spark-ignition engines with emission controls. These emission control systems consist of a number of engine modifications to conventional engines and an oxidation catalyst for hydrocarbon and carbon monoxide emissions control. The emissions data available from these development fleet tests show average emission levels at about the 1975 standards, and that HC and CO emissions generally increase with mileage because of catalyst deterioration. Extrapolation of these data suggests that many of these cars will not remain below the standards for 50,000 miles. Honda has developed and tested a three-valve, dual-carburetor, precombustion-chamber, stratified-charge engine. Toyo Kogyo has developed and tested a Wankel engine with a thermal reactor. These two alternative engines have shown the potential for certification for the 1975 model year in compact vehicles.

---

* For 1975 model year, these standards are 0.41, 3.4, and 3.1 grams per vehicle mile for hydrocarbons, carbon monoxide, and oxides of nitrogen, respectively. For 1976 model year, these standards are 0.41, 3.4, and 0.4 grams per vehicle mile for hydrocarbons, carbon monoxide, and oxides of nitrogen, respectively.

The emission control system most manufacturers are developing for conventional engines for the 1976 model year is the dual catalyst system. This system is a development of the 1975 conventional engine prototype systems, and further engine modifications and an additional catalyst (for $NO_x$ reduction) are required. At low mileage, vehicles equipped with this control system have met the 1976 standards, but the durability of current $NO_x$ catalyst is poor and is substantially inferior to the best oxidation catalysts now available.

The reasons for this deterioration are not well understood. There is less experience with $NO_x$ reduction catalysts than with oxidation catalysts. The activity of the $NO_x$ catalyst deteriorates more rapidly in tests on vehicles. Physical attrition of these catalysts continues to be a major problem, which is not encouraging since the duty cycle in the public's hands will be more severe than durability tests carried out to date. This system is complex, it requires precise control of engine operating conditions, and its potential for achieving adequate emission control in actual use is questionable.

Possible modifications to this system, such as the use of a feedback loop for air-fuel ratio control and the use of a single three-way catalyst, are being examined. One combination uses an oxygen sensor in the exhaust coupled with a fuel injection system to control the exhaust composition entering the three-way catalyst bed. While emissions levels at zero miles on small vehicles with this three-way catalyst system are promising, there are no emissions data over extended mileage with which to assess the system durability.

The most promising oxygen sensors are still in the development stage. It has yet to be shown that these sensors will have adequate durability with the average fuel contaminant levels expected in 1975-76. The U.S. automobile manufacturers have little field experience with electronic fuel injection (EFI) systems. Once feedback is introduced into fuel metering, EFI appears to have significant advantages over conventional carburetors. In the Panel's judgment, it is unlikely that a massive transfer to EFI can occur in the U.S. automotive industry in the time available. By late 1973, the 1976 emissions control system must be essentially frozen in all its major details and it would be necessary that considerable operating and durability experience would have to be acquired before that date.

Systems with thermal reactors and an $NO_x$ catalyst have shown the potential of meeting the 1976 standards at low mileage. These systems have many of the problems of the dual catalyst approach--complexity, need for precise control of engine operating conditions, inadequate durability--and have a higher fuel economy penalty.

Some of the unconventional engines now under development offer equivalent or better emission control potential with less performance penalties. Some of these systems appear to be more attractive in the long term.

The Wankel engine is lighter, more compact, has lower $NO_x$ emissions, and is expected to be cheaper to manufacture than a conventional engine. With a thermal reactor it has already demonstrated the potential for certification in compact vehicles in 1975 and has achieved $NO_x$ emission levels approaching the 1976 standard using exhaust gas recycle and fuel-rich carburetion. The fuel penalty compared with current conventional piston engines is substantial. While the Wankel engine is likely to be in mass production in 1975 and 1976, the quantity produced will be a small fraction of the expected total production of about 10 million per year.

Various types of stratified charge engines are being developed that show promise of emission control approaching the 1976 standards with good engine performance and with better fuel economy than current conventional engines. One of these, the Honda CVCC engine, has demonstrated the potential for certification in a compact car for 1975 without catalysts or exhaust gas recycle. Honda expects to have this engine in mass production by 1975. Honda has developed a version of their CVCC engine to emission levels close to the 1976 standards at low mileage in a compact car, but CVS-test fuel economy deteriorated substantially. It has not yet been shown that the Honda approach can meet the 1976 standards in a larger vehicle with acceptable performance penalties.

Experimental vehicles with open chamber fuel-injected stratified charge engines developed by Ford and by Texaco have demonstrated the potential of meeting the 1976 standards at low mileage using exhaust gas recycle for $NO_x$ control and oxidation catalysts for HC and CO. Research on the divided-chamber fuel-injected stratified charge engine concept shows it may have attractive low emissions characteristics also.

It is the Panel's view that when current performance is compared with the requirements for 1976 model year, these stratified charge engines are in early stages of development. The Honda system has not yet shown the potential for meeting the 1976 standards in a standard-size vehicle. For the other stratified charge engine concepts, many problems related to reliability and durability, as well as large-scale production feasibility remain to be solved. It is the Panel's judgment that large-scale production of these engines by 1976 in several engine sizes in different weight vehicles is not feasible.

## 2. Scope of Panel's Study

The Emission Control Systems Panel was formed by the National Academy of Sciences Committee on Motor Vehicle Emissions in August 1971 to examine in detail the emission controls being developed for spark-ignition engines in light-duty motor vehicles to meet the requirements of the 1970 Clean Air Amendments. The Panel has evaluated the efforts of all U.S. manufacturers of light-duty motor vehicles and of those foreign manufacturers with a significant fraction of the U.S. market. Members of the Panel have visited automobile manufacturers and other organizations developing emission control systems in the United States, Europe, and Japan. The Panel has followed closely the work of the CMVE Catalyst Panel, and some joint visits to catalyst developers were arranged. Appendix A lists the organizations consulted by the Panel during the course of its study. A questionnaire (shown in Appendix B) was sent to a number of automobile manufacturers in July 1972. Information from most automobile manufacturers on the latest developments in emission controls has been received continuously until about December 1, 1972. Information on the Honda engine has been updated to April 1973.

The scope of the Panel's study has included emission controls for both conventional reciprocating spark-ignition engines of the type currently in large-scale mass production and for unconventional spark-ignition engines such as Wankel rotary-combustion engines and stratified-charge engines. The Panel has attempted to evaluate the emissions levels achievable with mass production versions of the various emission controls now being actively developed to meet the requirements of the 1970 Clean Air Amendments. The durability of these emission control systems over extended mileage under conditions likely to be encountered in actual use has proved to be especially important. The Panel has also concerned itself with the vehicle performance, driveability, and fuel economy associated with the most promising of these control systems.

It is the judgment of the Panel that almost all the engines to be used in 1975 and 1976 model-year vehicles will be conventional reciprocating spark-ignition engines. The time available between now and the start of the 1976 model year production is too short to permit the introduction of novel engine concepts on the scale of 10 million units per year in several engine sizes and vehicle types. Extensive research, development, and design effort would be required before such a change would be practicable. Thus, modifications to existing engine designs and operating conditions, and the use of catalytic converters or thermal reactors in the exhaust system are the most effective methods available, in the short term, to reduce emissions from the bulk of 1975 and 1976 model-year production significantly below 1974 model-year emission levels.

It is anticipated that a small fraction of the 1975 and 1976 model-year vehicles sold in the United States will be Wankel rotary engines. Vehicles with one type of stratified-charge engine are also expected to be sold in the United States by at least one Japanese manufacturer in limited numbers. These types of engines may well be introduced slowly into the mass automobile market as other manufacturers gain experience with a new technology in the public's hands.*

The Panel therefore has examined both emission-control approaches applicable to conventional spark-ignition engines--the short-term technology--as well as more radical approaches that may be more attractive in the long term beyond the 1976 deadline.

---

*See the Report of the Panel on Manufacturing.

## 3. Background

Emissions from uncontrolled automobiles have come from the crankcase blowby gases, from fuel evaporation from the fuel tank, carburetor, and from the engine exhaust. The crankcase and evaporative losses were sources of hydrocarbons, but have now been effectively controlled. The emissions from the engine exhaust are a consequence of the details of the combustion process occurring inside the engine cylinder. Hydrocarbons (HC) and carbon monoxide (CO) result from incomplete combustion of the fuel-air mixture; oxides of nitrogen ($NO_x$) form in the high temperature burnt gases as the combustion process proceeds.

Considerable emission control on new vehicles has already been achieved by engine modification and improvements in engine design. Table 1 shows the evolution to date of the Federal Emission Control Program. Exhaust emission standards were first introduced for HC and CO on 1968 model-year vehicles and have since been progressively reduced. An understanding of factors affecting vehicle emissions has increased, the test procedure has been changed to determine more accurately the true contribution of the automobile to total urban emissions. Table 1 also summarizes the different test procedures used. Note that each emission standard is associated with a particular test procedure and that though standards for 1972 are stricter than those for 1970, the values are higher as a consequence of the different tests used.

Table 2 shows the estimated equivalents of the standards in Table 1 for a common test procedure, the latest 1975 CVS-CH test. The percentage reduction from an uncontrolled pre-1968 vehicle each standard represents is also given. Figure 1 shows the emission levels required to meet the standards, again on a percentage basis for the 1975 CVS-CH test procedure. For 1972 model-year vehicles,

Table 1 FEDERAL EMISSION CONTROL REQUIREMENTS FOR LIGHT-DUTY VEHICLES

| Model Year | Pre-1968[a] | | 1968 | 1970 | 1971 | 1972 | 1973 | 1975 | 1975 Interim[b] | 1976 |
|---|---|---|---|---|---|---|---|---|---|---|
| Test Procedure | FTP | CVS-C | FTP | FTP | FTP | CVS-C | CVS-C | CVS-CH | CVS-CH | CVS-CH |
| Emissions, g/mi | | | | | | | | | | |
| Hydrocarbons | 10 | 17 | 3.4 | 2.2 | 2.2 | 3.4 | 3.4 | 0.41 | (0.9) 1.5 | 0.41 |
| Carbon monoxide | 77 | 125 | 35 | 23 | 23 | 39 | 39 | 3.4 | (9.0)15.0 | 3.4 |
| Nitrogen oxides | 4-6 | 6 | NR | NR | NR | NR | 3.0 | 3.1 | (2.0) 3.1 | 0.4 |
| Evaporative Losses, g/test | 40 | | NR | NR | 6 | 2 | 2 | 2 | 2 | 2 |

NR--No Requirement.

[a] Uncontrolled vehicle except for crankcase blowby control.

[b] Values in brackets are for California. Other values apply for the rest of the nation.

## Table 1 (cont.)

Test procedures used to measure emissions:

FTP Federal Test Procedure - Driving cycle is the California 7-mode cycle repeated nine times. Pollutant concentrations in the exhaust are analyzed continuously throughout the 16-mi test. Concentrations in each mode are multiplied by weighting factors to give g/mi. Not a true mass emissions measurement.

CVS-C Constant Volume Sampling Procedure - A cold-start mass emissions test. Vehicle is soaked for 12 hr at 70°F before engine start-up. Driving cycle is 23-min, 7.5-mi nonrepetitive pattern. A constant fraction of the exhaust flow is collected in a bag, and concentration measurements at the end of the test give true mass emissions in g/mi.

CVS-CH Constant Volume Sampling Procedure - A cold-hot start weighted mass-emissions test. Vehicle is soaked for 12 hrs at 70°F before engine start-up. Driving cycle is 23 min pattern used in CVS-C. After a 10-min shut-down, engine is restarted and the first 505 sec of the driving cycle repeated. A constant fraction of the exhaust flow is collected: the first 505 sec in "cold transient" bag; next 864 sec in "stabilized bag"; repeat 505 sec in "hot transient" bag. Emissions in cold and hot transient bags are weighted 0.43 : 0.57 and added to emissions in stabilized bag to give true mass emissions.

Table 2 **Federal Exhaust Emission Standards in Table 1 Converted to 1975-76 CVS-CH Test Procedure**

| | HC[a] | | CO | | $NO_x$ | |
|---|---|---|---|---|---|---|
| Model Year | g/mi Exhaust | % Reduction Exhaust[b] | g/mi | % Reduction[b] | g/mi | % Reduction[b] |
| Average precontrol vehicle[c] | 12 | -- | 79 | -- | 6 | -- |
| 1968 | 6.2 | 48 | 51 | 35 | NR | |
| 1970 | 4.1 | 66 | 34 | 57 | NR | |
| 1972 | 3.0 | 75 | 28 | 65 | NR | |
| 1973 | NC | | NC | | 3.1 | 48 |
| 1975 | 0.41 | 97 | 3.4 | 96 | NC | |
| 1976 | NC | | NC | | 0.4 | 93 |

[a] Evaporative HC and crankcase HC for average vehicle in use in 1967 were equivalent to 3 g/mi and 1.9 g/mi, respectively.

[b] Percentage reduction standard represents from average precontrolled vehicle emissions.

[c] Average precontrol vehicle emissions means emissions from vehicle population per vehicle mile in year before standards were introduced. Evaluated in July 1967 for HC and CO and in July 1972 for $NO_x$.

NC -- no change.

NR -- no requirement.

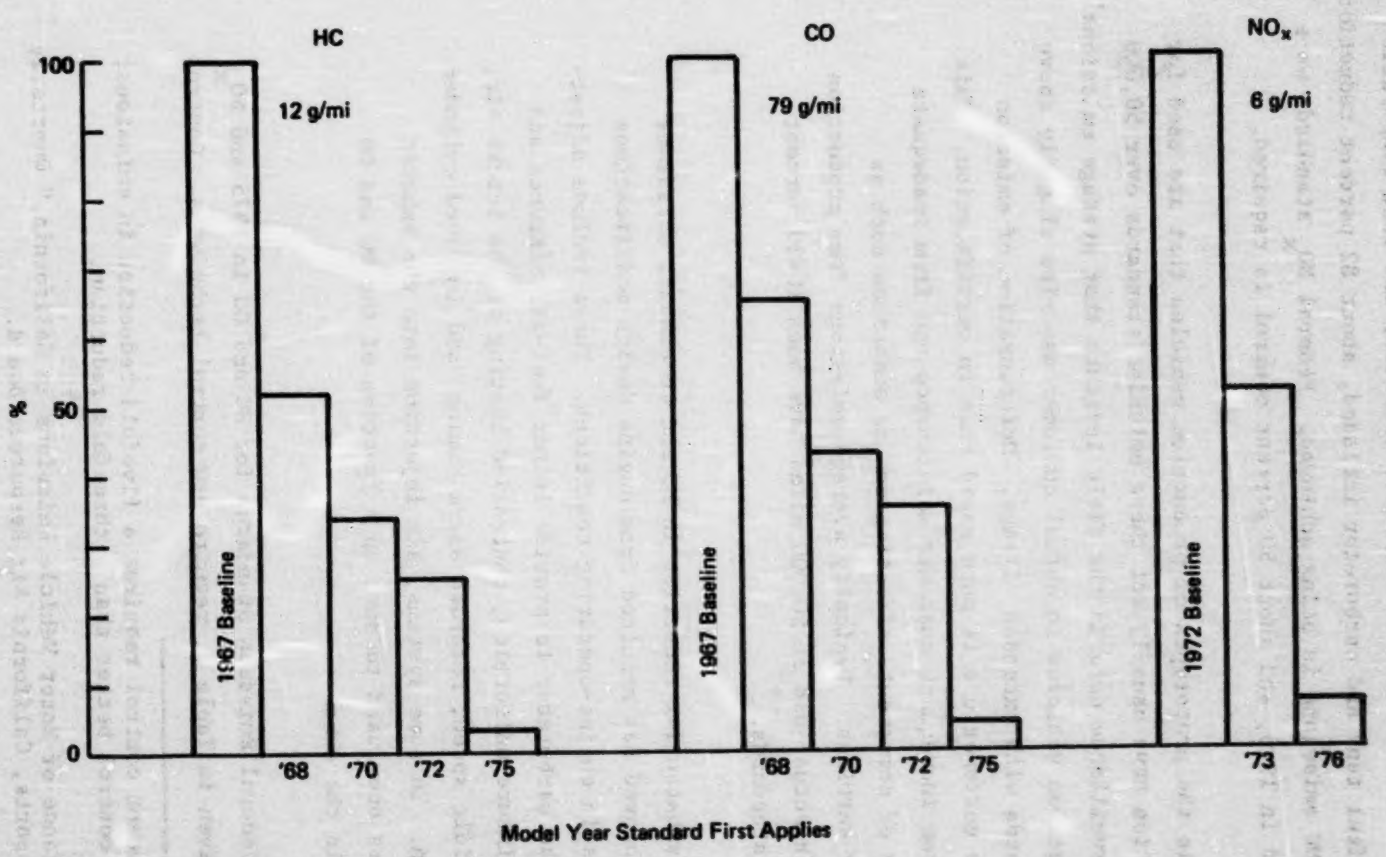


FIGURE 1 Federal exhaust emission standards in terms of 1975-76 CVS-CH test procedure.

about 75 percent control of HC and 65 percent control of CO are now required.* With control of crankcase emissions and fuel evaporation from the fuel tank and carburetor included, about 82 percent reduction in total HC emissions is being achieved. Federal $NO_x$ standards were introduced in 1973, and about 50 percent control is required.

While the prototypes of production vehicles that are used for certification have usually met these emission standards over 50,000 miles, surveillance data in the field indicate that average emissions from production vehicles in actual customer use rise slightly above the standards with extended mileage. Deterioration of emission control in customer use is more rapid than in certification. This results from inadequate customer maintenance and from inadequate durability of components affecting engine emissions such as carburetor settings. Typically average emissions from production vehicles in actual use at 50,000 miles have been 10-20 percent above the standards.**

The substantial reduction in HC and CO exhaust emissions already achieved has resulted from engine design modifications and changes in engine-operating conditions. These include adjustments to the carburetor to provide leaner fuel-air mixtures and improved mixture uniformity, controlled heating of the intake air, increased idle speed, retarded spark timing, and improved cylinder head design. In some systems, air injection into the exhaust manifold has been used to burn up a fraction of the HC and CO emissions in the exhaust.

The Federal Emission Standards for HC and CO in 1975 and $NO_x$ in 1976, given in Table 1, require new control techniques. Control of HC and CO emissions to the 1975 Standard levels appears to be unattainable with conventional engines through engine modifications of the type used to date. With conventional engines, HC and CO emissions from the engine itself are much higher than the 1975 Standards under all practical operating modes. Special reactors or converters located in the exhaust system will be required to burn up the emissions from the engine. $NO_x$ control to the 0.4 g/mi level will require exhaust gas recycling to the engine intake to reduce peak burnt gas temperatures and a $NO_x$ reduction catalyst. These new control techniques have a substantial impact on engine operation and performance.

---

*Eighty percent control requires a fivefold reduction in emissions; 70 percent control better than a threefold reduction.

**"Surveillance of Motor Vehicle Emissions in California," Quarterly Progress Reports, California Air Resources Board.

The effectiveness of these new control systems depends to a large extent on how well the individual components in the system have been integrated. It must be remembered that typical vehicle operation is a continuous sequence of different operating modes--engine start-up, idle, acceleration, cruise, deceleration, and so forth. To obtain satisfactory engine and vehicle performance over this wide range of modes, the air flow into the engine, the air-fuel ratio, and spark timing are all varied as engine loads and speeds change. The engine must also start and operate satisfactorily over the complete range of ambient temperatures, humidity, and altitude (which affects air density and hence metering) found throughout the United States.

The Federal emissions test that will be used to certify prototypes of the 1975 production vehicles incorporates a driving cycle including the common driving modes. It includes a cold-engine start after a 12-hour soak at between 60 and 86° F simulating an overnight shutdown, a continuous sequence of different driving modes over a 7.5 mi, 23-min average urban driving cycle, and a hot engine restart after a 10-min shutdown followed by a repeat of the first 505 sec of the 7.5-mi driving pattern. The emissions during the cold-start and hot-start portions of the test are then weighted as indicated in

Table 1 is an attempt to reflect the distribution of shutdown times occurring in average vehicle use. The overall emission control system must be optimized to operate effectively over the entire range of engine conditions covered in the test to achieve average HC, CO, and $NO_x$ emissions below the 1975-76 standards.

The cold-engine start and first few minutes of the test before the engine fully warms up appear to be especially important. In current automobile engines a choke is used to enrich the fuel-air mixture when the intake manifold is cold and fuel vaporization is poor. This enrichment is necessary to ensure that enough fuel is vaporized to provide a combustible mixture near the spark plug and to achieve reliable and safe vehicle operation. It results in high engine HC and CO emissions during the warm-up phase because not all this fuel can be fully burnt. In addition, the reactors in the exhaust that are used to burn up the HC and CO emissions from the engine itself also must warm up before they become effective. For typical 1975-76 control systems, it appears that HC and CO emissions during the first 2 min of the cold start test are greater than emissions during the last 21 min. The importance of adequate emission control of HC and CO during the warm-up phase is obvious.

Since the 1975 HC and CO standards require a 90 percent reduction below 1970 model-year vehicle emissions, and the 1976 $NO_x$ standard a 90 percent reduction below 1971 model-year vehicle emissions, major advances in emission control are required. The new components now being developed to achieve these reductions include exhaust thermal reactors, oxidizing and reducing catalysts, secondary air systems, exhaust gas recycle systems, electronic fuel injection, and air-fuel ratio feedback controls. In addition, substantial modifications to the carburetor, choke, intake manifold, cylinder-head geometry, ignition system, exhaust manifold, and exhaust pipe of a conventional engine are being considered.

In developing systems to meet the 1975 standards, automobile manufacturers have concentrated on control systems for conventional engines that can be modified to achieve greater $NO_x$ emission control. Most 1975 systems consist of engine modifications including exhaust gas recycle and an oxidizing catalytic converter as described in Chapter 5. However, California $NO_x$ standards of 1.5 g/mi may be imposed in 1975, and the Federal standard of 0.4 g/mi follows in 1976. These 1975 control systems for a conventional engine can be modified to achieve additional $NO_x$ control by increasing the amount of exhaust gas recycle, or by adding a $NO_x$ reducing catalytic converter to the exhaust system, or by a combination of both techniques.

Two such systems are under intensive investigation and development by automobile manufacturers for 1976. These are the dual-catalyst system, and the three-way catalyst system. In the dual-catalyst system, a separate $NO_x$ reduction catalyst is added to the exhaust system, between the engine and the oxidation catalyst. In the three-way catalyst system, a single catalytic converter, operating with precisely controlled engine exhaust gas composition, reduces the concentrations of all three pollutants, HC, CO, and $NO_x$ in the exhaust stream.

These are the only approaches to emission control to 1976 standard levels that have the potential of being in sufficiently large-scale production in August 1975 to meet new car demand. However, the performance of these catalytic converters is still inadequate, and there is a continuing emphasis on achieving low and stable engine emissions. For this reason, techniques for controlling emissions during the first part of the test when the engine is still cold, fuel-metering requirements, exhaust-gas recycle systems, and the potential for improved engine emissions control are still enormously important. The next chapter of this report, therefore, examines in detail the technology of the components that make up the emission control system for a conventional spark-ignition engine. The emphasis is primarily on engine emission controls; the details of catalytic converter performance are described in the CMVE Catalyst Panel report. The performance of complete emission control systems for conventional engines in experimental 1975 and 1976 vehicles is examined next in Chapters 5 and 6.

There are alternative types of spark-ignition engines that may have certain advantages compared to a conventional engine with sophisticated emission controls. The uncontrolled Wankel engine has higher HC and CO emissions, though engine $NO_x$ emissions are lower. Emission control techniques for the Wankel are similar to those for conventional reciprocating engines. However, only a relatively small number of vehicles with Wankel engines are likely to be mass produced in 1976 model year. Emission controls for Wankel engines are examined in Chapter 7.

Stratified-charge engines or high-turbulence engines with charge dilution are also promising alternatives. These achieve lower emissions than conventional engines through modifications to the basic combustion process inside the engine cylinder. There are several different engine concepts in this category at various stages of development; some of these concepts promise good emission control with minimum performance penalties when compared with conventional engines. These engines are reviewed in Chapter 8. Again these approaches are of longer-term significance, since such engines could not be in mass production by 1976 in sufficient quantity to meet total automotive demand.

## 4. Emission Control Technology

### Exhaust Emission Controls

Since emission control to the levels required for 1976 cannot be achieved in a conventional spark-iguition engine through engine modifications alone, intensive effort has been concentrated on developing exhaust-gas treatment devices. These include catalytic converters for reduction of $NO_x$ and oxidation of HC and CO, and thermal reactors. The function of these devices will be briefly reviewed.

### Reducing Catalytic Converter for $NO_x$

Reduction of nitric oxide in the exhaust gas in the presence of carbon monoxide and hydrogen can be accomplished with a suitable catalyst at typical exhaust-gas temperatures.

The catalyst is usually made up of a small mass of active material such as noble metal or a combination of transition and non-transition metals deposited on thermally stable support materials such as alumina. To prevent loss in catalytic activity due to mechanical damage, small spheric pellets or a honeycomb (monolithic structure) have been found the most suitable geometries. The catalyst is contained in a metal casing designed to direct the exhaust flow through the catalyst bed. Self-supporting metallic catalysts are also being developed.

For high conversion efficiency throughout the test cycle, the catalyst must attain its "light-off" temperature[*] as soon as possible after engine start-up. Considerable development work has therefore been done to reduce the density of the support material and increase the surface area of the active components. To maintain high catalytic activity with many of the catalysts being developed, the fuels employed must be low in concentration of various catalyst poisons such as lead, phosphorus, and sulfur.

---

[*] The temperature at which the catalyst becomes effective.

Because maximum $NO_x$ reduction occurs in a reducing atmosphere, the reducing converter must be placed upstream of the final oxidation catalyst or reactor, and the engine must be operated with a fuel-rich fuel-air mixture.

## Secondary Air System

The use of rich fuel-air mixtures requires the addition of air to the exhaust flow before the engine HC and CO emissions can be oxidized in a reactor or converter. An engine-driven air pump drives this air through a distribution manifold into the exhaust.

## Thermal Reactor

A thermal reactor is an enlarged exhaust manifold that bolts directly onto the cylinder head. Its function is to promote rapid mixing of the hot exhaust gas with the secondary air and retain the gases at a high enough temperature for sufficient time to burn most of the HC and CO. To achieve rapid warm-up after engine start, a low thermal inertia reactor core is desirable. Typically, a thin steel liner acts as the core of the reactor inside a cast-iron outer casing. Heat losses are held to a minimum, and the fuel-air mixture is enriched so that the chemical energy released inside the reactor in the oxidation process holds the core at temperatures of 1600-1800°F.

## Oxidizing Catalytic Converter

Oxidation of the HC and CO in the exhaust gas can be accomplished by means of catalysts at temperatures lower than those in a thermal reactor. A catalytic converter can be placed farther from the engine than a thermal reactor and can maintain its effectiveness without mixture enrichment to increase the chemical energy in the exhaust. As a consequence, the fuel economy penalty is lower. The oxidation catalyst is usually made up of a small mass of noble metal on an alumina support. Since HC and CO emissions are high during engine start-up when the engine is cold, rapid attainment of the oxidation catalyst's light-off temperature becomes especially important.

## Three-Way Catalytic Converter

When the exhaust gas composition is close to stoichiometric (just enough air is present in the fuel-air mixture to fully burn the fuel) the simultaneous removal of HC, CO and $NO_x$ can be achieved with a suitable catalyst material. These catalysts are similar in construction to the noble metal reducing and oxidizing catalysts. The three-way catalyst requires precise control of air-fuel ratio to maintain high conversion efficiencies for all three pollutants.

## Carburetion

The precise metering of the fuel and air supply to gasoline automotive engines has become much more important in recent years because the mixture ratio is a critical parameter affecting the exhaust composition and the functioning of exhaust-treating devices. The carburetor is required, under all engine operating conditions, to meter a predetermined mixture ratio of fuel and air. Varying air temperature and barometric pressures are sources of metering error. The fuel also varies in composition and physical properties according to brand, production tolerances, and temperature, with attendant effects on the mixture ratio.

Important improvements to provide increased metering accuracy have been made in the design and production control of carburetors in recent years. However, the conventional carburetor is beset with many difficult problems, among which are:

1. Fuel evaporates from the float bowl, which must be maintained at ambient pressure.*

2. The carburetor is necessarily associated with a fuel-wetted intake manifold, which makes difficult the equal distribution of the fuel to all the engine cylinders.

3. It is difficult to cut off, or properly control, the fuel flow during the engine deceleration mode. This problem is due, in part, to the fuel-wetted manifold.

4. Airbleeds are used to assist the fuel-metering function. The use of air for this purpose makes fuel metering more difficult to predict and control and can be a cause of unsteady fuel discharge to the engine.

5. Complex additional devices are required to provide compensation for varying inlet air pressure and temperature (or altitude compensation).

To help overcome these difficulties, most 1975-76 model carburetors have been redesigned to achieve better air-fuel ratio control and maintain good cold-start performance of the engine. Improved idle-mixture needle controls, factory set off-idle air adjustment screws, and new fast-idle cams are representative of these alterations. Most carburetors will also be temperature-and-altitude-compensated because the air-fuel ratio changes by 5 percent with an air temperature change of 50°F and decreases by 1¼ percent for every 1000-ft elevation. Disregarding the demands during extreme accelerations and deceleration, the newly designed carburetors are capable of maintaining tolerances of ±3 percent of the set air-fuel ratio. This approaches the fuel metering accuracy required for the dual catalyst 1976 control systems where the air-fuel ratio must be held between about 0.5 and 1.5 air-fuel ratios richer than stoichiometric (between about 13.8 and 14.5 for a typical gasoline composition) to achieve adequate $NO_x$ reduction in the first catalytic converter.

---

*Carburetor fuel evaporation is now successfully controlled.

Considerable design work remains to be done to ensure durability with these finely adjusted carburetors. Most manufacturers are considering factory-sealed, tamper-proof settings because it will be impossible to achieve the required adjustments with the crude means of the average mechanic. The durability of these factory-set adjustments is unknown and is considered to be a problem.

A number of new carburetor concepts have been proposed and tested. The aim of these devices is to supply small-diameter fuel droplets and more uniformly dispersed mixtures to the engine. With this improved dispersion, vehicles can operate with leaner mixtures and thus lower hydrocarbon, carbon monoxide and nitric oxide exhaust emissions should result. Atomization and mixing of fuel with air in high velocity converging-diverging nozzles with controllable throat area (e.g. the Dresserator), ultrasonic generators, and heated nozzles have been considered to achieve the desired results. Some of these concepts have shown the ability to reduce engine emissions below current conventional carbureted engine levels. So far, however, these improvements have been matched by the advanced carburetors described above.

## Cold-Start Emission Controls

With 1975-76 catalyst-based emission control systems, over half of the carbon monoxide and hydrocarbon emissions occur during the cold-start and engine warm-up portions of the drive schedule in the CVS emission test. The oxidizing converter is cold during this phase and is not effective in reducing these initial high engine emissions. Figures 2 and 3 represent typical test results with GM

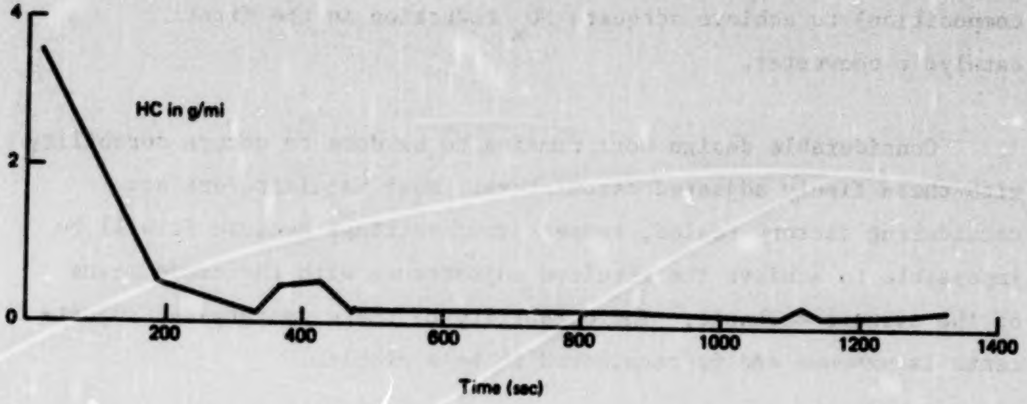


**FIGURE 2** **Emissions during the first 7.5 miles of the CVS test, showing importance of HC during cold start.**

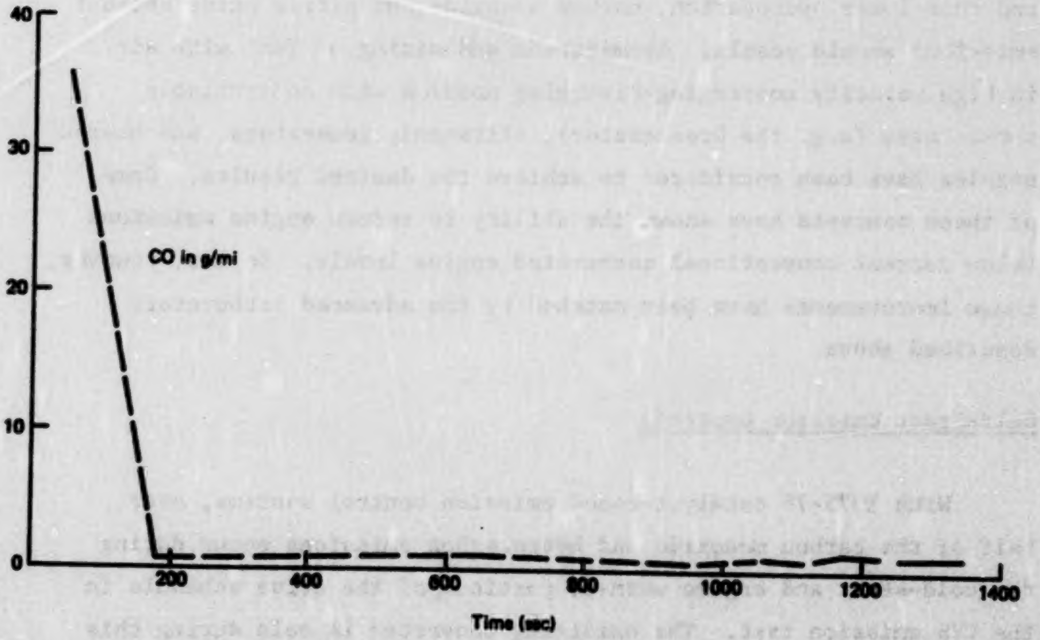


**FIGURE 3** **Emissions during the first 7.5 miles of the CVS test, showing importance of CO during cold start.**

experimental 1975 vehicles during the 1972 Federal Test Procedure for hydrocarbon and carbon monoxide. Despite the overall low levels of emissions, 60 percent of the total hydrocarbons and 80 percent of the total carbon monoxide were emitted during the first 2 minutes of the 23-min test cycle. The high initial hydrocarbon and carbon monoxide emissions result from the enrichment of the fuel-air mixture that is required during cold start to compensate for the low volatility of cold gasoline. This excess fuel is not fully burned in the combustion process or in the oxidation catalytic converter and is thus discharged into the atmosphere. Although the $NO_x$ catalyst is also cold and ineffective during start-up, $NO_x$ emissions tend to be lower because rich mixtures and lower charge temperatures suppress the formation of $NO_x$.

Because of these very high HC and CO emissions during cold start, considerable development effort has been spent in a number of cold-start controls and procedures. The following are some representative concepts that have been investigated by several manufacturers:

Dual Fuel Cars: These cars use liquid petroleum gas (LPG) during the starting and warm-up phase and switch to regular fuel after the engine has reached normal operating temperatures. Because of the high volatility of LPG, start-up fuel enrichment is not necessary and consequently cold-start emissions are virtually eliminated. This concept has been dropped from consideration despite excellent emission results because of hazard and complexity reasons.

Supplemental Heat for the Catalyst: The concept here is to use auxiliary heaters to bring the oxidation catalyst rapidly to the operating temperature. The reduction in emissions did not justify the cost of the heating system.

Cold Storage Controls: In this system hydrocarbons are stored in an activated charcoal container during cold start and are purged into the converter as soon as it has reached its operating temperature.

Because no absorbing material for carbon monoxide has been found, the use of this concept is considered to be of limited value.

Modification of Fuels: It has been suggested that the fuel distillation characteristics be modified to provide higher volatility during cold start. Fuels with a well-controlled distillation curve, i.e., one with higher mid-range and back-end volatilities could satisfy both the cold and warm running requirements of the engine. A number of programs are now under way to examine whether such modifications are practical and economically feasible.

In the prototypes of their 1975 and 1976 systems, most manufacturers have elected to modify the cold-start procedure and carburetor in order to reduce start-up emissions. Specifically, they have achieved start-up with leaner fuel-air mixtures by preheating the air, by improving the mixture control in the carburetor, and by shortening the choking period without seriously impairing cold-engine operation and driveability. Most prototypes include air preheat systems and modified choke operation.

The purpose of preheating the air is to vaporize a higher fraction of the cold fuel which, in turn, allows leaner engine operation and shorter choking period during warm-up. The air-preheat system, which has been incorporated in most 1972 American-made cars, will be used in most 1975-76 models. It uses a sheet metal heat exchanger fixed to one exhaust manifold to preheat air during start-up. A thermostatically controlled valve in the air cleaner snorkel shuts off cold air during the start-up period and allows the heated air to enter the carburetor. As the air temperature increases, the control valve mixes the cold and hot air to maintain 100°F at the carburetor inlet. On hot days and at high power, the 100°F is exceeded. The air preheat system allows reduction of the choking time to 1 min or less (from several minutes without it). The air-preheat system is simple and has proven to be reliable.

In addition to this air-preheating system, 1975-76 emission controls have provision to supply heat to the intake manifold to promote further evaporation of the cold fuel droplets. This is accomplished by using a heat exchanger, or so-called "stove" between the carburetor and the exhaust manifold crossover. The cold fuel droplets make contact with a hot surface and vaporize. With this system, choking times have been reduced to less than 30 sec while maintaining adequate driveability.

A variety of problems with the exhaust-gas control valve, gaskets, and coke formation on the heat exchanger remain to be solved to ensure that production units can attain the emission reduction predicted by experimental designs. Durability of the system has not been evaluated, but there are no major technical difficulties anticipated in achieving adequate durability.

Most 1975-76 model carburetors have been redesigned to achieve better air-fuel ratio control and maintain good cold-start performance of the engine. A quick-acting choke will be used to lean-out the mixture as early as possible after start-up. Electrical or mechanical timing devices will be used to shorten choking time from several minutes for precontrol cars to typically less than 30 sec. These timing devices are either auxiliary heaters to provide heat to the choke coil or friction-type dashpot timers, e.g., rubber pistons. Because of their simplicity, these devices are reliable, effective and durable.

In combination, these controls have been most effective in lowering hydrocarbons and carbon monoxide emissions during cold start. Particularly, carbon monoxide start-up contributions have been lowered from 80 percent to 40 percent of the CVS cold-start cycle emissions.

**Electronic Fuel Injection**

There has been interest for many years in Electronic Fuel Injection

(EFI) as an alternative to the float carburetor. In automotive applications, the fuel is usually injected into the intake port just ahead of the intake valve. This is less difficult than cylinder injection and has the important advantage of utilizing the high-velocity flow through the intake valve to aid the mixing of the fuel and air.

Nearly all gasoline-injection systems determine the fuel requirements of the operating engine by measuring rpm, manifold pressure and temperature, and ambient pressure. From these inputs the EFI electronic module determines the required fuel quantity, which is supplied to electromagnetic nozzle valves from a fuel supply at a constant regulated pressure of approximately 30 psia. Fuel quantity is modulated by changing the fuel injection time duration. Each cylinder has its individual injection valve. Fuel is injected in the intake port toward the intake valves.

New EFI systems are under development. One proposed improvement employs a variable area mechanical air flow meter that activates a potentiometer. This, like a Venturi carburetor, is a more direct means of measuring air flow than the current intake manifold pressure-temperature and engine rpm measurements. The performance advantage of the EFI system lies in the dynamic response characteristics, in better volumetric efficiency, and the ability to compensate readily for changes in exhaust pressure.

Precise metering of the fuel and air, as in the case of the carburetor, is difficult to achieve. The metering system employs an electronic control device, many sensors, a fuel pump, and solenoid-controlled injection nozzles. The complete system requires many precision components. Contacts made with carburetor manufacturers, automobile manufacturers, and producers of electronic fuel injection equipment indicate that current EFI systems do not provide substantial improvement in air-fuel ratio control over the advanced-design carburetors.

EFI systems are in production on several European cars. Field experience with these systems showed a high component failure rate initially, though the performance has now been improved.

The advantage of EFI over current carburetors in small cars is in performance characteristics and fuel economy, i.e., in increased power output (particularly for high rpm high performance engines), in better fuel economy for high speed driving, and in improved driveability, particularly with manual-shift transmissions. The large American engines that operate at lower rpm and mostly with automatic transmissions derive less advantage from EFI than do small European engines. Also, until recently, fuel economy has not been as important as in high-fuel-cost Europe. For these reasons, American manufacturers have not been able to justify the higher initial cost of electronic fuel injection.

There is general agreement that fuel injection systems alone do not provide enough reduction in emissions to meet the 1975 and/or 1976 Federal requirements without exhaust-treating devices. The U.S. automotive industry has so far taken the position that the higher cost of the injection system compared with a carburetor is not justified. With further development and cost reduction of EFI equipment, rising fuel cost, and the increasing use of electronics to control other engine functions, there may well be a trend toward fuel injection systems. One factor that may accelerate this trend is the potential of achieving more precise control of air-fuel ratio with a feedback system.

## Feedback Systems for Air-Fuel Ratio Control

The need for more precise control of exhaust-gas composition in a conventional engine using a reducing catalyst for $NO_x$ control, or a 3-way catalyst for simultaneous control of HC, CO and $NO_x$, has led to the investigation of feedback systems. One method under development in several European and American companies that has met with some success is a closed-loop system of fuel metering. In such a system, an oxygen sensor is used to detect low levels of oxygen in the exhaust stream and to supply an error feedback signal either to an EFI module or to a specially constructed carburetor. Another method being investigated is to use this feedback signal to control exhaust gas composition in the exhaust manifold through air or fuel addition.

The sensors now being developed consist typically of an electrochemical solid electrolyte oxygen concentration cell in the shape of a closed tube contacted at the inner and outer surfaces with thin porous platinum electrodes. The tube material is stabilized zirconium dioxide, which shows adequate ionic conductivity at temperatures above approximately 400°C. The inner part of the tube is exposed to the atmosphere and senses an oxygen partial pressure of approximately 3 psi; the outer part senses the partial pressure of oxygen in the exhaust. When the air-fuel mixture changes from fuel-rich to oxygen-rich (around the stoichiometric composition), the oxygen concentration at the sensor surface changes from a very small to a much larger value. This change in concentration produces a strong step-like voltage change of about 1 volt across the electrodes. This voltage change is the result of the large concentration changes of oxygen and therefore will always occur at near-stoichiometric or chemically correct air-fuel ratio regardless of temperature and composition of the other constituents of the exhaust stream. Quantitatively, the voltage swing will occur within the air-fuel ratio range of ±0.1 about the stoichiometric value, the precise value depending on fuel composition.

If this sensor is used in a feedback loop, either with EFI or with a special carburetor, the strong error signal will tend to maintain the engine operating air-fuel ratio within the narrow limits of ±0.1 about the stoichiometric value. The response time of the sensor is much faster than the response of the exhaust to changes in air-fuel ratio because of the long transmission delay between the fuel injection point and sensor location. This mismatch requires careful design of the control loop to avoid oscillation and unstable control conditions. One approach to this problem is locating the sensor close to the exhaust ports and providing adequate damping in the electronic module. The EFI module is also easily modified to convert the error signal of the sensors into proportional changes of the fuel-injection time.

Alternatively, the feedback signal can be used to directly control the composition of the exhaust gas in the exhaust manifold. Additional fuel can be added to the manifold exhaust gas if the mixture is too lean; air can be added if the mixture is too rich.

The primary air-fuel ratio control currently required with the EFI system or a carburetor must be within ±5 percent of the stoichiometric value. Existing sensor feedback systems do not correct for deviations outside this range since they lose control authority. Current EFI and advanced carburetors can achieve this degree of air-fuel ratio control during steady-state operation but deviate significantly outside the ±5 percent range during transient vehicle modes such as acceleration and deceleration. To obtain full benefit from the sensor-feedback system, improvements in the performance of the basic EFI or carburetor are necessary.

The use of the oxygen feedback sensor will require the use of some electronic circuitry. The EFI system is therefore well suited to operate with the $O_2$ sensor and appears to provide a faster response. Note, however, that these sensors do not operate when cold and do not, therefore, improve cold-start emissions.

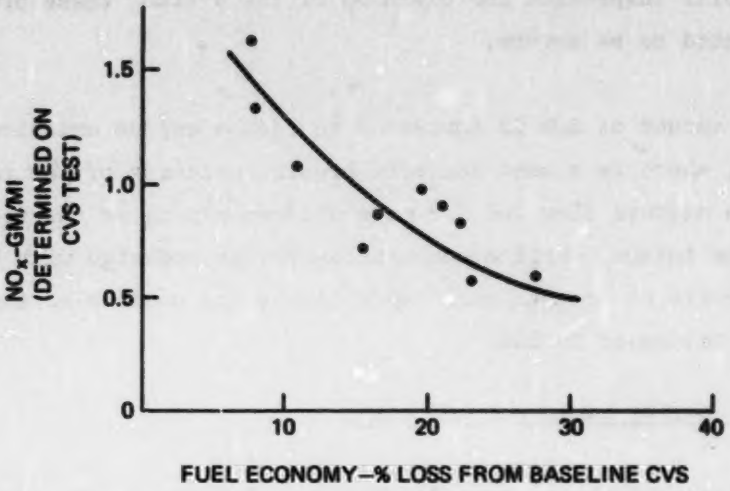
The durability of the oxygen sensors now available is inadequate, and the life in a vehicle is only a few hours. The major problems are thermal shock, erosion of the electrodes, and maintaining good electrical contacts with the sensor. In addition, bench tests have shown that the sensor can be poisoned by lead, sulfur, phosphorus, and other impurities. Considerable development will therefore be required before the sensor and feedback system is ready for mass production.

If the durability and poisoning problems are solved, the oxygen sensor could make an important contribution to lowering emission levels and could improve durability of the catalysts in the exhaust system by avoiding large variations in exhaust composition and temperature during the operation of the engine.

The sensor is expected to be cheap and the development target is a life of about 12,000 miles. The sensor could then be exchanged like a sparkplug. One sensor is adequate for 4-and-6 cylinder engines; a V-8 engine would require two sensors, one for each bank of cylinders.

### Exhaust Gas Recycle (EGR)

The most extensively developed technique for reducing engine $NO_x$ emissions is the recycling of a fraction of the exhaust to the engine intake. The recycled exhaust gases dilute the fresh mixture and reduce peak combustion temperatures and $NO_x$ formation rates. EGR generally results in reductions in flame speed with attendant fuel-economy penalties. Further disadvantages of EGR are the loss in engine power and the reduction in tolerable air-fuel ratio variations consistent with smooth engine operation. To compensate for these problems, the use of EGR is generally accompanied by some mixture enrichment to maintain adequate driveability, which results in a further fuel penalty. In most systems, EGR is cut out at wide-open throttle and idle operation. Figure 4 indicates the fuel economy penalty with a conventional engine as EGR and mixture richness are increased to obtain lower $NO_x$ emissions.



**$NO_x$ CHANGED BY VARYING FUEL, EGR AND SECONDARY AIR METERING**

**VEHICLE DESCRIPTION**

- **–302-2V AUTO. GALAXIE**
- **–PORT LINERS**
- **–THERMAL REACTORS**
- **–NOBLE METAL CATALYSTS**
- **–AIR CLEANER EGR**
- **–OTHER MODIFICATIONS**

**FIGURE 4** **$NO_x$ Emissions versus Fuel Economy.**

EGR was introduced in most 1973 model year vehicles to bring $NO_x$ below 3 g/mi. Experience from the durability testing of these EGR systems indicates that plugging of the recycle line and control valve with leaded fuels is a significant problem. But with unleaded fuels and with regular inspection and cleaning of the system, these problems are not expected to be severe.

As the amount of EGR is increased to reduce engine emissions below 3 g/mi, there is a need for more precise matching of the recycle flow to fresh mixture flow and for more uniform mixing of the recycled exhaust in the intake. Engine combustion-chamber redesign with higher turbulence levels to promote more rapid combustion would also improve the engine's tolerance to EGR.

## Potential for Engine Emissions Reduction

As a result of these controls, engine emissions can be expected to be reduced below the current production engine levels. Typical levels from current new production vehicles are given in Table 3. The top two lines are measured emissions from a General Motors 1972 production audit. Both sales-weighted mean emissions and the standard deviation are given. The magnitude of the standard deviation indicates the spread in emissions about the mean value. This spread occurs as a result of difference in items such as brake setting, variations in transmissions, engine friction, carburetor settings, and stacking up of engine tolerances. The best GM division has been able to reduce both mean engine emissions and the spread in emissions, through improved production control as indicated in the second line in Table 3.

With the addition of a quick-heat manifold and an improved carburetor with a quick-acting choke, these HC and CO engine emissions can be improved. However, use of EGR to reduce $NO_x$ emissions generally requires some mixture enrichment to compensate for the decreased

**Table 3 Engine Emissions at Low Mileage: Mean and Standard Deviation**

| | Emissions in g/mi[a] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| | Mean (S.D.) | Mean (S.D.) | Mean (S.D.) |
| GM 1972 production[b] audit | 1.7 (0.64) | 22 (8.3) | ~4 (~1)[c] |
| Best GM division 1972 production | 1.2 (0.32) | 16 (6.2) | ~4 (~1)[c] |
| Panel estimate of best engine emissions, lean carburetion[d] | 1 (0.15) | 10 (3) | 2.5 |
| Panel estimate of engine emissions, rich carburetion[e] | 1.5 | 25 | 1.5 |

[a] 1972 CVS-C test procedure.

[b] 3656 vehicles tested.

[c] California 7-mode test emissions multiplied by 2.

[d] Standard-size engine, standard-size car, with quick heat manifold, improved carburetor, quick-acting choke, and EGR.

[e] Same as d and with air injection into the exhaust manifold.

ignitability and flame speed, and engine HC and CO emissions rise. The last two lines in Table 3 are Panel estimates of reasonable engine emissions goals at low mileage for standard-sized engines in standard weight vehicles for lean and rich carburetor settings.

The developments required to achieve these goals are satisfactory integration of a quick-heat manifold, improved carburetor, and quick-acting choke with the engine, and improved engine tolerance to EGR. Whether engine $NO_x$ emissions below about 2.5 g/mi will be required for 1976 emission control systems depends on the activity and durability of $NO_x$ catalysts.

Deterioration factors for engine emission controls obtained from the GM 1972 certification fleet are shown in Table 4. Hydrocarbon and CO emissions deteriorated by about 25 percent over the 4000- to 50,000-mile test. The spread in deterioration is from no deterioration to about a 40 percent increase in emissions.

The magnitude of the standard deviation of these emission results underlines the necessity for averaging of emissions to determine compliance with the 1970 Clean Air Amendments. (See Chapter 10.)

Table 4 Deterioration in Engine Emissions over 50,000 miles[a]

| | Low Mileage Emissions, g/mile[b] | 50,000-mile Deterioration Factor[c] | Range in Deterioration Factor |
|---|---|---|---|
| HC | 2 | 1.26 | 1.0-1.4 |
| CO | 12 | 1.23 | 1.0-1.4 |
| $NO_x$ | ~4 | 1.12 | 1.0-1.2 |

[a] 1972 GM certification data.

[b] 1972 CVS-C test, except for $NO_x$ (which is California 7 mode test multiplied by 2).

[c] Deterioration factor is emissions at 50,000 miles divided by emissions at 4000 miles.

## 5. Status of 1975 Conventional Engine Emission Control Systems

Almost all the automobile manufacturers have developed similar prototype emission controls systems for their 1975 model-year vehicles. Only Honda and Toyo Kogyo, with its Wankel engine, are pursuing radically different approaches. The major U.S. manufacturers are now assembling and testing fleets of vehicles equipped with the complete emission control system to evaluate different promising catalyst materials and obtain data on system durability before the final production design details are frozen.

These emission control systems for conventional engines typically consist of:

1. An improved carburetor to provide more accurate fuel metering, with compensation for air-density changes due to altitude change, and with an electrically powered choke that comes off quickly at ambient temperatures of about 70°F.
2. A quick heat intake manifold designed to promote rapid fuel evaporation after engine start-up.
3. An electronic ignition system to eliminate the wear and other problems of current distributors (which, due to inadequate maintenance, are a common cause of increased engine emissions) and to allow easier spark-timing control.
4. An exhaust gas recycle (EGR) line and control valve designed to recycle about 10 percent of the exhaust flow to hold $NO_x$ emissions below 3 g/mi.
5. An air pump that injects air into the exhaust ports.
6. A catalytic converter in the exhaust system that burns up the HC and CO emissions from the engine.

Figure 5 shows a schematic of a typical 1975 system.

For some manufacturers, the current fleet tests represent the first extensive evaluation of the complete engine emission controls

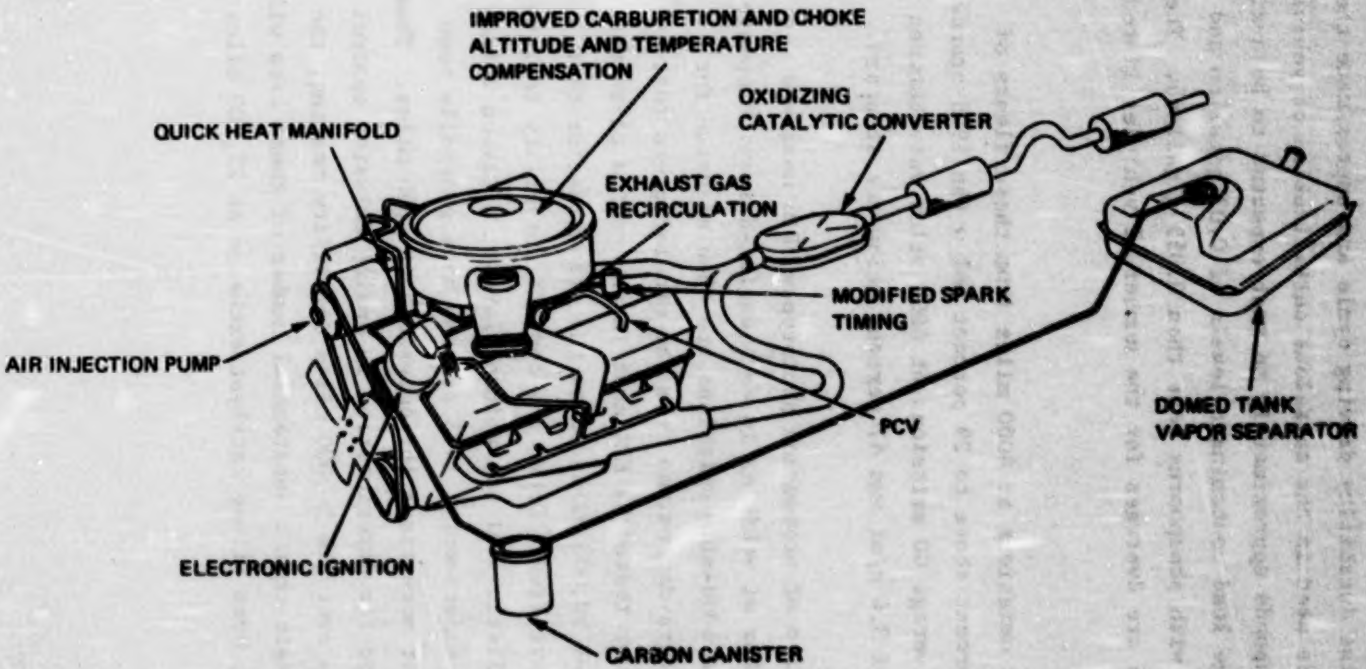

IMPROVED CARBURETION AND CHOKE
ALTITUDE AND TEMPERATURE
COMPENSATION
QUICK HEAT MANIFOLD
OXIDIZING
CATALYTIC CONVERTER
EXHAUST GAS
RECIRCULATION
MODIFIED SPARK
TIMING
AIR INJECTION PUMP
DOMED TANK
VAPOR SEPARATOR
PCV
ELECTRONIC IGNITION
CARBON CANISTER

FIGURE 5 Schematic of GM 1975 system.

with the best oxidation catalyst materials now available. Results from several manufacturers' development fleets are summarized in Table 5. These tests follow the durability driving cycle and approximate the maintenance procedure used in the emissions certification of vehicles; the fuel used corresponds approximately to that expected to be available in 1975 (average lead contaminant levels of 0.03 g/gallon and 0.04 percent sulfur with phosphorus less than 0.055 g/gallon). The emissions in Table 5 are averages for the number of vehicles listed at each mileage.

The average HC emissions at 4000 miles from these fleets of cars vary from 12 percent above to 29 percent below the 1975 standard of 0.41 g/mi. The average CO emissions at 4000 miles vary between about the standard of 3.4 g/mi and 47 percent below the standard.

For certification of production prototypes, EPA measures emissions from a number of vehicles in each engine-driveline combination at 4000 miles. These 4000-mile emissions are then adjusted for deterioration by factors determined from the manufacturers tests over 50,000 miles. Each car tested by EPA must in any engine class have projected emissions at 50,000 miles below the standards for that engine class to be certified. Under the correct durability testing conditions, with realistic fuel contaminant levels, emission values at 50,000 miles with experimental 1975 systems have generally been about a factor of 2 or more times the emissions at 4000 miles. Thus, when allowance is made for deterioration in engine emission control and catalyst activity over the 50,000 miles durability testing, the data in Table 5 indicate that a substantial number of these cars will exceed the standards, even if one catalyst exchange at 25,000 miles is permitted.

Table 5 Emissions Performance of Major Manufacturers 1975 Model-Year Development Fleets

| Manufacturer | Vehicle Weight Range, lb | Engine Size Range, CID | No. of Vehicles | Mileage | Emissions in g/mi[a] HC | CO | $NO_x$ |
|---|---|---|---|---|---|---|---|
| Ford[b] | 4000 - 5000 | 250 - 460 | 8 | 4000 | 0.46 | 3.2 | 2.7 |
| | | | 7 | 36000 | 0.73 | 5.2 | 2.2 |
| Ford[c] | 4000 - 5000 | 250 - 460 | 6 | 4000 | 0.34 | 3.3 | 2.2 |
| | | | 5 | 36000 | 0.40 | 2.6 | 2.4 |
| General Motors[b] | 2750 - 5500 | 140 - 550 | 30 | 4000 | 0.34 | 2.3 | 2.0 |
| | | | 17 | 12000 | 0.42 | 2.6 | 2.0 |
| | | | 7 | 24000 | 0.39 | 2.2 | 1.8 |
| Nissan[b] | 2750 | 98 | 5 | 4000 | 0.29 | 1.8 | 1.0 |
| | | | 5 | 16000 | 0.50 | 2.2 | 0.95 |
| | | | 1 | 24500 | 0.48 | 3.8 | 0.95 |
| Toyota[d] | 2500 | 97 | 6 | 4000 | 0.35 | 2.9 | 1.4 |
| | | | 4 | 12000 | 0.52 | 5.5 | 2.1 |
| | | | 3 | 24000 | 0.66 | 9.0 | 1.2 |

**Notes**

[a] 1975 CVS-CH test procedure. Durability driving schedule, maintenance, and fuel used approximate those anticipated in 1975 certification procedure. Emissions averaged over all vehicles tested at that mileage. No catalyst replacements were made during any of these tests. Data received up to November 1972.

[b] Emission control system: engine modifications, air pump, oxidation catalyst, EGR.

[c] Emission control system: engine modifications, air pump, 2 oxidation catalysts; EGR.

[d] Emission control system: engine modifications, manifold reactor, air pump, oxidation catalyst, EGR.

## 6. Status of 1976 Conventional Engine Emission Control Systems

### Dual-Catalyst Systems

The control system on which most development effort has been concentrated uses two catalyst beds to clean up the engine emissions before exhausting to the atmosphere. A typical system layout is shown in Figure 6. The bed closest to the engine is used to remove $NO_x$. It is operated under net reducing exhaust gas conditions (about 1 to 2 percent carbon monoxide in the exhaust gas, which corresponds to a slightly rich carburetor calibration). Air is then added to the exhaust stream between the catalyst beds, and much of the remaining HC and CO emissions are removed in the second catalyst, the oxidation bed. The two catalytic beds may be in separate containers, as shown in Figure 6, or they may be packaged in a single container. The system is a logical development of the 1975 control system described in Chapter 3. Since the performance to date of these emission controls is inadequate, these 1976 systems are experimental in nature, and many details of the configuration have yet to be finalized. The major changes from the 1975 prototype systems, in addition to the $NO_x$ catalytic converter are

Richer Carburetor Setting. The fuel air mixture burned in the engine must contain a slight excess of fuel to provide net reducing exhaust conditions (1-2 percent CO, which corresponds to an air-fuel ratio of 13.8-14.5) in the $NO_x$ catalyst bed. This results in a fuel economy penalty and higher CO and HC loading on the oxidation catalyst.

Increased EGR. An $NO_x$ catalyst efficiency (fractions of the $NO_x$ emissions entering the converter that are removed) of 86 percent (averaged over the test cycle), will be required over the 50,000 mile durability testing for a 1975 vehicle with engine emissions under 3 g/mi to meet the 0.4 g/mi 1976 standard. While the initial activity

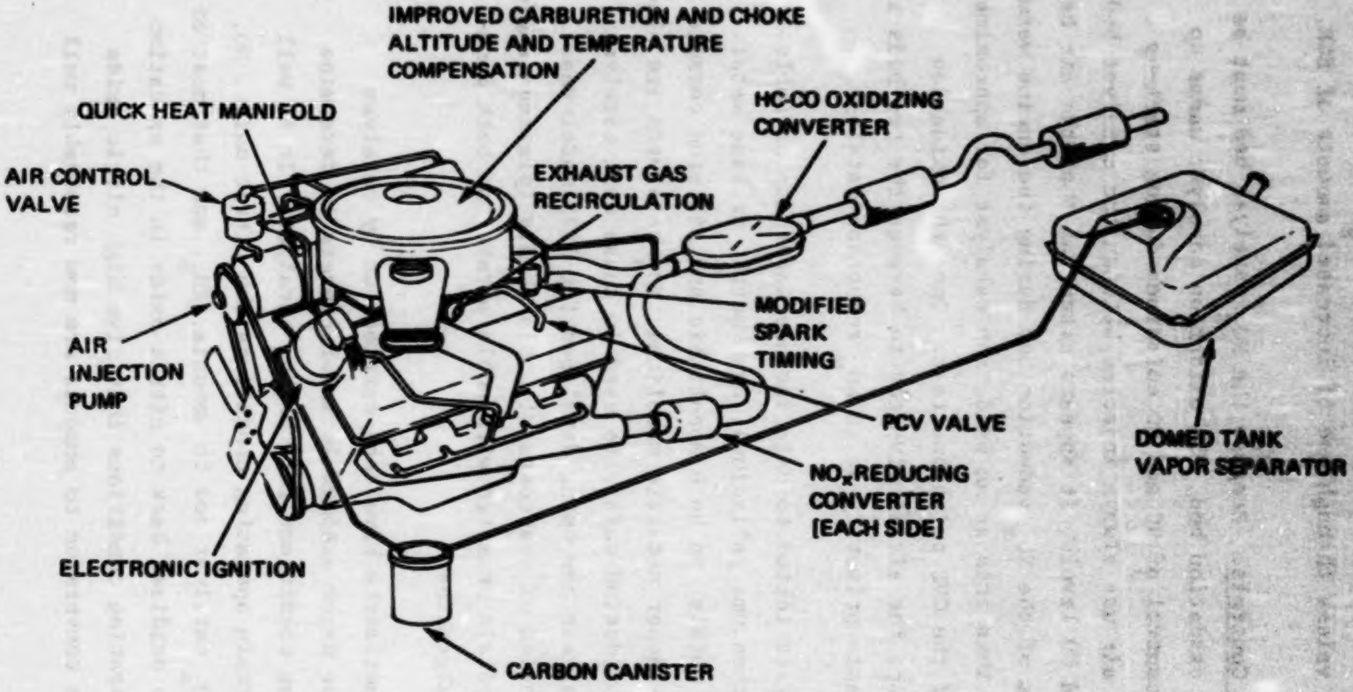

IMPROVED CARBURETION AND CHOKE ALTITUDE AND TEMPERATURE COMPENSATION
QUICK HEAT MANIFOLD
HC-CO OXIDIZING CONVERTER
AIR CONTROL VALVE
EXHAUST GAS RECIRCULATION
MODIFIED SPARK TIMING
AIR INJECTION PUMP
PCV VALVE
DOMED TANK VAPOR SEPARATOR
NO$_x$ REDUCING CONVERTER [EACH SIDE]
ELECTRONIC IGNITION
CARBON CANISTER

FIGURE 6 Schematic of GM 1976 dual-catalyst system.

of the best $NO_x$ catalysts now available exceeds this value, very few $NO_x$ catalysts when tested over several thousand miles have maintained this high an activity. Thus it is likely that engine $NO_x$ emissions must be decreased from 1975 values through use of increased amounts of EGR.

Air Injection Controls. Because the $NO_x$ catalyst bed must be placed ahead of the oxidation bed, the oxidation catalyst warms up more slowly. Thus control of HC and CO emissions during start-up would be delayed if air was always injected between the catalyst beds. To reach 1976 HC and CO levels, it appears essential that the air be diverted to upstream of the $NO_x$ reduction bed during the engine warm-up phase. The $NO_x$ bed thus acts as an oxidation catalyst for approximately the first 100 sec of the CVS emissions test. Once the oxidation catalyst is warmed up, the air is diverted to between the two beds and the first catalyst acts primarily as an $NO_x$ reduction catalyst.

The $NO_x$ catalysts tested to date include washcoats of noble metal (platinum, ruthenium, palladium), base metal, or base metal promoted with noble metals, on both monolithic and pelleted ceramic substrates. Nickel-copper metallic monolithic $NO_x$ catalysts are also being tested. The oxidation catalysts used in these dual catalyst systems are the catalysts now being developed for 1975 model-year vehicles. These consist of washcoats of noble metals (platinum and/or palladium) or base metals promoted with noble metals, on both monolithic and pellet substrates.

Laboratory experiments have been carried out by catalyst manufacturers and the major automobile manufacturers to determine the optimum operating conditions for the $NO_x$ catalyst. It is well known that under certain operating conditions the nitric oxide, NO, is reduced in the $NO_x$ catalyst bed to ammonia, $NH_3$, and that most of this ammonia is then oxidized back to nitric oxide in the oxidation catalyst. Those operating conditions that give high nitric oxide reduction and little conversion to ammonia are now reasonably well understood. For example, the fuel-air ratio must be controlled to give between 1 and 2 percent CO in the engine exhaust gas stream. Richer mixtures give increasing ammonia formation. The conversion of NO to $NH_3$ also depends on the catalyst temperature. A higher operating temperature reduces ammonia formation. Table 6 gives approximate bed operating temperatures for 90 percent conversion of the entering $NO_x$ and the percentage conversion of nitric oxide to ammonia. Higher temperatures than those shown give greater conversion efficiencies and less ammonia formation. Actual catalysts are combinations of several elements designed to give improved performance.

Generally, $NO_x$ catalysts must operate at higher temperatures than oxidation catalysts to avoid $NH_3$ formation and achieve the high conversion efficiencies required to meet the 1976 standards. For this reason they are normally placed close to the engine in the toeboard location, as indicated in Figure 6. Because they must operate at a higher average temperature, they are more susceptible to damage from overheating. In addition, the oxidation catalyst downstream from the $NO_x$ catalyst is subjected to higher loadings of HC and CO because of the richer carburetor setting, and it therefore operates at a higher temperature than is typical in 1975 systems.

Because there are two catalysts in series, the pressure drop across the catalyst bed is a more important constraint since it significantly affects the engine output. For this reason, monolithic $NO_x$ catalysts having a lower pressure drop have been tested more extensively, though there appear to be no significant emissions performance differences between pelleted and monolithic catalysts.

The automobile manufacturers are now testing experimental vehicles with the more promising $NO_x$ catalysts identified by laboratory tests. The vehicle configuration is still exploratory. Some of the tests used EGR to reduce engine $NO_x$ emissions, others

**Table 6 Effect of Catalyst Material on Operating Temperature and Ammonia Production**

| Catalyst Material | Approximate Minimum Operating Temperature for 90 percent $NO_x$ Conversion | Approximate Ammonia Production, % |
|---|---|---|
| Ruthenium | 700° F | 5 |
| Platinum | 1200° F | 15 |
| Base metal | 1400° F | 5 |

have not. The effects of changes in the position of the $NO_x$ catalyst bed, bed size, carburetor fuel-air ratio control, percent EGR, duration of air flow to the $NO_x$ bed are only beginning to be explored. With the best catalysts now available, it has been possible to meet the 1976 standards with a number of experimental vehicles at low mileage. Several examples of the best low mileage emissions data available to date are shown in Table 7.

Only a few of these vehicles have been tested to evaluate durability. Before attempting extensive durability tests, most manufacturers are working to optimize the performance of the system to reduce low mileage emissions to values at least 50-60 percent below the 1976 standard levels and to improve vehicle driveability and hold performance losses to a minimum. The experience with oxidation catalysts to date indicates that a factor of 2 increase in emissions over the 50,000-mile durability testing is the minimum deterioration that can be expected. $NO_x$ catalyst durability is substantially inferior to the best oxidation catalyst durability, thus these goals are not unreasonably low.

The results of the most promising durability tests in some of these dual catalyst vehicles are summarized in Table 8. Emissions are shown as a function of mileage. Where engine emissions data are available, the average catalyst conversion efficiencies over the entire CVS-CH driving cycle can be estimated and are shown in the table. Conversion efficiency is the percentage of entering emissions removed in the converter. These data show that the initial high conversion efficiency rapidly deteriorates.

The causes of this rapid deterioration in $NO_x$ catalyst efficiency are not yet quantitatively understood. How much of the deterioration is due to inadequate control of fuel-air ratio in the engine and the consequent temperature fluctuations in the catalyst bed is not yet known. Thermal degradation of the catalyst can occur

Table 7 Examples of Best Low Mileage Emissions Measurements with Dual-Catalyst Systems on Experimental 1976 Vehicles

| Company | Vehicle Weight, lb | Engine Size, ~CID | EGR | Emissions in g/mi[a] |  |  | Catalyst Data |
|---|---|---|---|---|---|---|---|
|  |  |  |  | HC | CO | $NO_x$ | (a) HC/CO (b) $NO_x$ |
| American Motors |  | 258 |  | 0.27 | 5.7 | 0.55 |  |
| Esso | 4500 | 350 | No | 0.09 | 1.0 | 0.2 | (a) Engelhard<br>(b) Gould GEM |
| Volvo | 3500 | 85 | Yes | 0.19 | 2.2 | 0.4 | (a) Base, pellet<br>(b) Base, pellet |
|  | 3500 | 85 | Yes | 0.41 | 3.4 | 0.38 | (a) Noble, monolith<br>(b) Noble, monolith |
| General Motors | 4500 | 350 | Yes | 0.24 | 1.7 | 0.15 | (a) UOP, platinum, pellet<br>(b) Gulf, monolith |
|  | 4500 | 350 | Yes | 0.42 | 3.1 | 0.21 | (a) Air products, pellet<br>(b) Gulf, pellet |
|  | 4500 | 350 | Yes | 0.17 | 1.0 | 0.19 | (a) UOP, platinum, pellet<br>(b) Johnson-Matthey, monolith |
|  | 4500 | 350 | Yes | 0.21 | 1.0 | 0.22 | (a) UOP, platinum, pellet<br>(b) Johnson-Matthey, monolith |
|  | 4500 | 350 | Yes | 0.37 | 1.8 | 0.27 | (a) UOP, platinum, pellet<br>(b) GM, pellet |
| Chrysler |  | 360 | No | 0.17 | 3.0 | 0.5 | (a)<br>(b) Noble, monolith |
|  |  | 360 | No | 0.23 | 2.5 | 0.52 | (a)<br>(b) Base |
|  |  | 360 | Yes | 0.34 | 3.9 | 0.44 | (a)<br>(b) Noble, pellets |

Table 7 (cont.)

| Company | Vehicle Weight, lb | Engine Size, CID | EGR | Emissions in g/mi[a] | | | Catalyst Data |
|---|---|---|---|---|---|---|---|
| | | | | HC | CO | $NO_x$ | (a) HC/CO (b) $NO_x$ |
| Ford | 4000 | 250 | No | 0.45 | 2.9 | 0.38 | (a) Engelhard, monolith<br>(b) Promoted Base, pellet |
| | 5000 | 351 | No | 0.43 | 2.4 | 0.27 | (a) Engelhard, monolith<br>(b) Gould, GEM |
| | 4000 | 250 | No | 0.52 | 3.7 | 0.39 | (a) Engelhard, monolith<br>(b) ICI, pellet |
| | 5000 | 351 | Yes | 0.48 | 3.3 | 0.39 | (a) Engelhard, monolith<br>(b) ICI, pellet |
| Daimler-Benz | | 350 | Yes | 0.20 | 1.4 | 0.33 | (a) Chemico, base, pellet<br>(b) Chemico, base, pellet |
| | | | Yes | 0.15 | 1.2 | 0.3 | (a) Noble, monolith<br>(b) Noble, monolith |
| Nissan | 2750 | 98 | Yes | 0.1-0.2 | 0.4-1.2 | 0.3 | (a)<br>(b) Johnson-Matthey, noble, monolith |
| Johnson-Matthey Ricardo | 2700 | 110 | No | 0.17 | 1.8 | 0.25 | (a) Johnson-Matthey, noble, monolith<br>(b) Johnson-Matthey, noble, monolith |
| Volkswagen | 2500 | 98-104 | Yes[b] | 0.38 | 2.2 | 0.64 | (a) Monolith, noble<br>(b) Monolith, noble |
| | 2500 | 98-104 | Yes[b] | 0.49 | 4.9 | 0.46 | (a) Monolith, noble<br>(b) Monolith, noble |
| | 2500 | 98-104 | Yes | 0.82 | 4.0 | 0.57 | (a) Monolith, noble<br>(b) Monolith, noble |

Table 7 (cont.)

| Company | Vehicle Weight, Lb | Engine Size, CID | EGR | Emissions in g/mi[a] | | | Catalyst Data |
|---|---|---|---|---|---|---|---|
| | | | | HC | CO | $NO_x$ | (a) HC/CO (b) $NO_x$ |
| Toyota | 2500 | 97 | Yes[b] | 0.39 | 2.7 | 0.5 | (a) Palladium, pellet<br>(b) American Oil, base, pellet |
| | 2500 | 97 | Yes[b] | 0.29 | 3.0 | 0.54 | (a) Palladium, pellet<br>(b) American Oil, base, pellet |
| | 2500 | 97 | Yes | 0.39 | 3.7 | 0.39 | (a) Palladium, pellet<br>(b) Toyota, platinum, pellet |

---

[a] 1975 CVS-CH test procedure. Data were usually averages of several tests and were received up to November 1972.

[b] Emission-control systems include a manifold thermal reactor before the $NO_x$-reduction catalyst.

Table 8 **Emissions As Function of Mileage for Durability Tests on Dual-Catalyst Systems**

| Manufacturer, Vehicle[a] | Catalysts (a) HC/CO (b) $NO_x$ | Mileage | Emissions, g/mi[b] HC | CO | $NO_x$ | $NO_x$ Catalyst Efficiency[c], % |
|---|---|---|---|---|---|---|
| **GENERAL MOTORS** | | | | | | |
| 4500 lb | (a) UOP, noble, | 0 | -- | -- | 0.22 | 78[d] |
| 350 CID | pellet | 1000 | 0.32 | 1.7 | 0.42 | 58[d] |
| Chevrolet | (b) Gulf, noble, | 7000 | 0.39 | 3.0 | 0.45 | 55[d] |
| EGR | pellet | 13000 | 0.52 | 4.8 | 0.73 | 27[d] |
| 4500 lb | (a) UOP, noble | 0 | 0.21 | 1.0 | 0.21 | 79[d] |
| 350 CID | pellet | 7000 | 0.47 | 1.8 | 0.59 | 41[d] |
| Chevrolet | (b) Johnson-Matthey, | | | | | |
| EGR | noble, monolith | | | | | |
| 4500 lb | (a) UOP, noble, | 0 | 0.36 | 1.8 | 0.28 | 72[d] |
| 350 CID | pellet | 4000 | 0.57 | 4.1 | 0.51 | 49[d] |
| Chevrolet | General Motors | | | | | |
| EGR | Research, | | | | | |
| | pellet | | | | | |
| **FORD** | | | | | | |
| 5000 lb | (a) Engelhard, mono- | low | 0.3 | 1.5 | 0.56 | 78 |
| 351 CID | lith | 3000 | 0.33 | 1.5 | 0.49 | 80 |
| Ford | (b) monolith | 6000 | 0.48 | 2.6 | 0.70 | 71 |
| EGR | | 9000 | 0.72 | 1.9 | 0.89 | 63 |
| | 8-10 g of | 12000 | 0.66 | 3.6 | 0.75 | 64 |
| | platinum[e], dual- | 16000 | 0.66 | 5.4 | 1.3 | 46 |
| | bed converter. | 20000 | 0.82 | 3.8 | 1.5 | 37 |
| 5000 lb | (a) pellet | low | 0.35 | 3.8 | 0.68 | 70 |
| 351 CID | (b) pellet | 1000 | 0.61 | 3.3 | 0.99 | - |
| Ford | | 2000 | 0.59 | 3.6 | 1.25 | - |
| EGR | Dual-bed converter | 6000 | 0.68 | 4.2 | 1.72[f] | 25 |

Table 8 (cont.)

| Manufacturer, Vehicle[a] | Catalysts (a) HC/CO (b) $NO_x$ | Mileage | Emissions, g/mi[b] HC | CO | $NO_x$ | $NO_x$ Catalyst Efficiency,[c] % |
|---|---|---|---|---|---|---|
| **FORD (cont.)** | | | | | | |
| 4000 lb<br>250 CID<br>Ford<br>No EGR | (a) -<br>(b) ICI, pellet | low | 0.52 | 3.7 | 0.39 | 89 |
| | | 4000 | 0.65 | 5.2 | 0.48 | 86 |
| **NISSAN** | | | | | | |
| 2750 lb<br>98 CID,EGR | (a) Noble, pellet<br>(b) Johnson-Matthey noble, monolith | 0 | 0.19 | 0.5 | 0.28 | 70 |
| | | 3000 | 0.32 | 1.1 | 0.7 | 37 |
| | | 7300 | 0.34 | 1.7 | 1.1 | 6 |
| | | 13900 | 0.67 | 2.7 | 1.1 | |
| 2750 lb<br>98 CID, EGR | (a) Noble, pellet<br>(b) Johnson-Matthey noble, monolith | 0 | 0.1 | 0.4 | 0.3 | 84 |
| | | 5200 | 0.33 | 2.2 | 1.3 | 30 |
| 2750 lb<br>98 CID, EGR | (a) Noble, pellet<br>(b) Johnson-Matthey noble, monolith | 0 | 0.17 | 1.2 | 0.27 | 67 |
| | | 3100 | 0.38 | 1.8 | 0.5 | 38 |
| **TOYOTA** | | | | | | |
| 2500 lb<br>97 CID<br>Reactor, EGR | (a) Palladium, pellet<br>(b) American Oil, base, pellet | 0 | 0.39 | 2.7 | 0.5 | - |
| | | 12000[g] | 0.46 | 2.8 | 0.82 | - |
| | | 20000[g] | 0.50 | 3.1 | 0.93 | - |
| 2500 lb<br>97 CID<br>Reactor, EGR | (a) Palladium, pellet<br>(b) American Oil base, pellet | 0 | 0.29 | 3.0 | 0.54 | - |
| | | 12000[g] | 0.49 | 3.5 | 0.81 | - |
| | | 28000[g] | 0.52 | 5.7 | 1.5 | - |

Table 8 (cont.)

| Manufacturer Vehicle[a] | Catalysts (a) HC/CO (b) $NO_x$ | Mileage | Emissions, g/mi[b] HC | CO | $NO_x$ | $NO_x$ Catalyst Efficiency[c], % |
|---|---|---|---|---|---|---|
| **TOYOTA (cont.)** | | | | | | |
| 2500 lb | (a) Palladium, | 0 | 0.39 | 3.7 | 0.39 | - |
| 97 CID | pellet | 4000 | 0.45 | 4.2 | 0.51 | - |
| Reactor, EGR | (b) Toyota, | 8000 | 0.40 | 4.3 | 0.94 | - |
| | platinum | 12000 | 0.59 | 4.4 | 1.09 | - |
| | pellet | 16000 | 0.31 | 4.3 | 0.38 | - |

---

[a] Emission Control System includes engine modifications, air pump, $NO_x$ catalytic converter, oxidation catalytic converter, and EGR and manifold reactor where noted.

[b] 1975 CVS-CH test procedure. Data received up to November 1972.

[c] $NO_x$ catalyst efficiency is percent $NO_x$ removed in catalytic converter.

[d] $NO_x$ catalyst efficiency estimated from approximate engine $NO_x$ emission of 1 g/mi.

[e] Catalyst judged by vendor not to be available in commercial quantities.

[f] EGR system failure.

[g] Emissions at these mileages measured after maintenance.

due to damage to the surface structure caused by overheating. The presence of an oxidizing atmosphere even for short periods of time when the catalyst is hot is known to be detrimental especially to the nickel-copper alloy metallic catalysts. The loss of catalytic material both from noble metal and base metal $NO_x$ catalysts has also been observed and is probably due to oxidation.

It is clear that poisoning of the active catalyst material by contaminants in the fuel is the cause of part of the observed deterioration. During the last two years it has become evident that the oxidation catalysts being tested in 1975 prototype vehicles deteriorate as a consequence of the trace quantities of lead, phosphorus, and other elements in lead-free fuels and lubricants. It is anticipated that as a result of EPA regulations, the lead-free fuel available in 1975 and 1976 will have average contaminant levels of about 0.03 g lead/gallon, less than 0.005 g phosphorus/gallon, and about 0.04 percent sulfur by weight. It is not known how severely these contaminant levels will affect the activity of the different $NO_x$ catalysts now being evaluated. Laboratory tests on a noble metal $NO_x$ catalyst containing platinum and other metals showed lead poisoning of comparable magnitude to that observed with platinum oxidation catalysts. Sulfur also affected the activity of this $NO_x$ catalyst at levels of 0.04 percent by weight or more. However, the Gulf catalyst containing ruthenium appears in bench tests to be much more resistant to lead poisoning. Also, $NO_x$ catalysts may have the ability to partially recover from sulfur poisoning if operated in an oxidizing atmosphere at high temperatures. However, as explained earlier, these conditions may result in loss of catalytic material and damage to the catalyst surface structure.

Because of these concerns, the ability to control air-fuel ratio within narrow limits with these dual catalyst systems is critical. As was described in Chapter 4, the improved carburetors being developed for 1975-76 are expected initially to hold the air-fuel ratio within the ±3 percent range required during steady state operation. The durability of the carburetor adjustments and the magnitude of the variations outside this ±3 percent range that occur during rapid acceleration and deceleration are not yet known. Electronic fuel injection without a feedback system does not offer any substantial advantages in dealing with these problems. However, the sensor-feedback concept described in Chapter 4 could be used to control air-fuel ratio, and thus exhaust gas composition, with the dual catalyst emission control system. The resulting system would be complex. An air pump is required to supply secondary air upstream of the oxidation catalyst and air must be diverted to upstream of the $NO_x$ reduction catalyst during the cold-start portion of the test. The elimination of exhaust gas composition excursions outside the desirable operating window of the catalysts would be expected to improve catalyst life. There is as yet insufficient experience with EFI and a feedback control integrated with a dual-catalyst system to evaluate its effectiveness.

Many automobile manufacturers report continuing difficulties with physical attrition of both $NO_x$ and oxidation catalysts. The problems appear especially severe with small 4-cylinder engines, which operate at higher rpm and with more vibration in the exhaust manifold. Monolithic catalysts frequently last less than 1000 miles before the monolith is shaken to pieces in its container. The same catalyst and container may last tens of thousands of miles on a different vehicle. Pelleted catalysts on small vehicles also show greater attrition than on large vehicles. These types of problems raise the question as to whether the accelerated testing used to determine the durability of control systems is really representative of the treatment vehicles receive in the public's hands. With accelerated testing, the number of engine cool-down periods is substantially reduced, and the effects of water condensation in the exhaust system, start-ups at temperatures below freezing, effects of unusual road surfaces, etc., are rarely encountered. There must therefore be continuing concern as to whether the physical durability of these converters can be adequately demonstrated before production designs are committed.

## Three-Way Catalyst System

A single-bed catalyst that under carefully controlled operating conditions will simultaneously reduce all the emissions, HC, CO, and $NO_x$, is under development by several catalyst manufacturers. The current catalysts of this type must be operated with the exhaust gas composition close to stoichiometric. An air-fuel ratio of about 14.5 ± 0.1 is required to obtain simultaneously high CO, HC, and $NO_x$ conversion. Deviations in air-fuel ratio outside these limits result in poor $NO_x$ conversion on the lean side and poor HC and CO conversion on the rich side.

If such a catalyst can be successfully incorporated into a vehicle and can be proved to possess adequate durability, a simpler system than the dual catalyst system would result. Since there is enough oxygen present in the exhaust gas, the air pump is no longer required. One catalyst bed is eliminated, and the difficulties of heating up the two catalyst beds rapidly to control cold-start emissions are simplified. Vehicle driveability is good with a stoichiometric fuel-air mixture, and the fuel economy could be reasonably close to optimum.

However, a feedback control will be required to maintain the air-fuel ratio at 14.5 ± 0.1 throughout the entire engine operating range. One promising type of control with an oxygen sensor has already been described in Chapter 4. It is under development for both fuel-injection systems and carbureted systems as a trimming device. The fuel-injection system seems the more logical approach and appears to have a faster response.

Developments on feedback systems have been proceeding most intensively in Europe, where the performance gains of fuel-injection systems on smaller, higher-speed engines are more significant. Test results on six different European vehicles with between 1.5 and 2 liter displacement, with Bosch L-jetronic fuel-injection systems and oxygen sensors, 5 percent EGR and noble metal monolithic three-way catalysts are summarized in Table 9. Also shown are data from Bendix, again with a compact car. These results are at low mileage; durability data are not yet available.

The major disadvantage of stoichiometric operation is that the engine $NO_x$ levels are close to a maximum. Without EGR, engine $NO_x$ emission at this fuel-air ratio would be 6-8 g/mi and hence very high $NO_x$ conversion efficiencies in the catalyst bed would be required. It appears likely that EGR will be used to achieve some engine $NO_x$ emissions control.

Several parallel developments will have to take place before the oxygen sensor-feedback control-catalyst system can be considered more than a promising concept. First the oxygen sensor required to control the air-fuel ratio must be shown to be durable in the exhaust environment of an operating vehicle with commercially available lead-free fuels. Next the primary air-fuel ratio control, EFI or an advanced carburetor, must be improved to be within ±5 percent of stoichiometric for all engine operating modes. The durability of the catalyst in the three-way system must then be demonstrated. The effects of poisoning by fuel contaminants and temperature fluctuations on the catalyst activity and size of the required air-fuel ratio operating window are unknown at this time.

## Systems with Thermal Reactors

A substantial amount of experience has been obtained on emission control systems that incorporate thermal reactors. In such systems, the reactor--which replaces the conventional exhaust manifold--is used

Table 9 **Low-Mileage Emissions from Compact and European Vehicles Equipped with Three-Way Catalyst Systems**

| | Emissions in g/mi[a] | | |
|---|---|---|---|
| | HC | CO | $NO_x$ |
| Six Volkswagen vehicles with Bosch EFI and $O_2$ sensor; 5% EGR, and noble metal monolithic three-way catalysts. | | | |
| 60-test average | 0.15 | 2.2 | 0.21 |
| Range | 0.1 - 0.25 | 1.1 - 3.3 | 0.1 - 0.35 |
| Bendix tests on 2500-lb vehicle, 150-CID 4-cylinder engine, EFI and $O_2$ sensor, 8% EGR | | | |
| 6-test average | 0.24 | 2.8 | 0.35 |
| Range | 0.18 - 0.30 | 2.1 - 3.2 | 0.31 - 0.37 |

[a] 1975 CVS-CH Test Procedure. Data received up to November 1972.

to burn up the HC and CO emissions from the engine. Some systems combine a thermal reactor with catalysts; some use a thermal reactor alone. Engine emissions controls are used as in the catalytic converter systems.

There have been two basic versions of systems using a thermal reactor only: fuel-rich and fuel-lean systems. The fuel-rich system results in less $NO_x$ formation but only at the expense of substantially poorer fuel economy. The lean system does not require air injection so that it has the advantage of being simpler. Fuel-rich reactor cars typically operate in the range of air-fuel ratios from 11:1 to 13:1, while lean reactor cars operate at air-fuel ratios of 17 to 19:1 depending upon the degree of exhaust-gas recirculation. These ranges of operation result in acceptable but not always good driveability.

Exhaust manifold reactors are bolted to the cylinder head in the position of the normal exhaust manifolds, and air is injected into the exhaust ports. Typically, an internal liner separates the hot inner gases from a cooler outer shell. This is intended to minimize the heat losses and thereby maximize the efficiency of the reactor. The exhaust gases and injected air enter the tubular core first and then flow through the outer shell before entering the conventional exhaust system. The turbulence level and flow are designed to optimize mixing; this is accomplished by the use of turbulence-inducing baffles and control of the location and size of outlet passages.

A major difficulty in thermal reactor systems has been achieving high enough gas temperature inside the reactor to burn up the engine HC and CO emissions. In the rich reactor approach, the chemical energy in the exhaust is used to obtain core gas temperatures of up to 1800°F. In the lean reactor, gas temperatures are significantly lower and the degree of emissions control achieved is less.

It is also important to achieve rapid warm-up of the reactor after the cold engine start-up. For this reason, the thickness of the steel core is held to a minimum. Spark retard is also used to enhance rapid warm-up of the reactor by increasing exhaust gas temperatures.

With a single reactor, the gases leaving the reactor contain excess oxygen, and it is not possible to follow the reactor with an $NO_x$ catalyst. Thus control of $NO_x$ must be achieved by EGR and lean or rich carburetor calibrations. It has not been possible to achieve 0.4 g/mi $NO_x$ emissions and the HC and CO standards with these systems. More complex combinations of reactors and catalysts are discussed later.

The emissions of the best experimental thermal reactor systems developed to date have not been low enough to meet the standards for 1975 or 1976. The performance of Wankel engines with thermal reactors is discussed in Chapter 7. Theoretically, the possibility exists of increasing the mixing rate of injected air and exhaust gases in the reactor for rich reactor systems, minimizing heat losses, and/or increasing the residence time to a point where CO and HC concentrations become very low and meet the standards. In practice this has not been achieved. The best emissions results obtained with thermal reactor systems at low mileage are shown in Table 10. Rich reactor systems achieve better emissions control than lean reactor systems, but have a much higher fuel economy penalty and have more severe durability problems since the reactor core operates at higher temperatures.

The improved emissions control shown by the Esso reactor and the latest version of the duPont reactor were achieved by raising the reactor core temperatures. This obviously increases the severity of the materials durability problem. Neither GM, Esso, nor duPont has established the durability of their improved systems over extended mileage. However, with lower operating temperatures and higher

Table 10 Low-Mileage Emissions of Thermal Reactor Systems

| | Emissions g/mile[a] | | | |
|---|---|---|---|---|
| | HC | CO | $NO_x$ | Fuel Economy Loss, % |
| **Rich Reactor Systems** | | | | |
| duPont[a] | 0.05 | 9.2 | 0.51 | 21 |
| Esso[b] | 0.1 | 4.6 | 0.7 | 17-22 |
| Ford (IIEC) | 0.3 | 9.0 | 1.4 | 20 |
| General Motors Cars | | | | |
| Modified duPont | 0.17 | 8.1 | 0.78 | 28 |
| ER-1 | 0.14 | 10.3 | 0.77 | 32 |
| SV | 0.2 | 6.0 | 0.6 | 38 |
| Vega | 0.2 | 5.4 | 0.7 | 24 |
| Ceramic | 0.11 | 11.7 | 0.86 | - |
| V8 Central | 0.13 | 4.6 | 0.8 | 31 |
| Lean Reactor Systems | | | | |
| Ethyl | 0.36 | 4.0 | 1.8 | 12 |

---

[a] 1972 CVS-C test procedure was used, except where noted [b].

[b] 1975 CVS-CH procedure was used. Data received up to November 1972.

emission levels, the durability of the thermal reactor system is more promising. Table 11 indicates the emission control already demonstrated over extended mileage.

Systems combining one or more thermal reactors with catalytic converters are also being developed. In most of these systems the thermal reactor bolted to the cylinder head is used to achieve partial burn-up of the engine HC and CO emissions to reduce the load on the oxidation catalyst downstream.

General Motors is developing a reactor-catalyst combination called a triple-mode system. The aim of the system is to avoid damaging the $NO_x$ and oxidation catalyst beds by overheating during engine operation at high load. At about 55 mph vehicle speed, the dual catalyst system is bypassed through a thermal reactor. General Motors data indicate that HC, CO, and $NO_x$ emissions from the vehicle are all higher during the bypass mode. At lower speeds, the bypass is sealed with a valve.

This system approaches the 1976 standards at low mileage as shown in Table 12; its durability has yet to be established. The system is more complicated than the dual catalyst system and the development of an effective valve is a formidable problem since the bypass must be sealed tight when not in use. The emissions at high vehicle speed are higher than values obtained with the dual catalyst system alone. The claimed, but yet to be demonstrated, advantage is that catalyst life would be extended by the elimination of prolonged high temperature catalyst operation.

Another reactor-plus-catalyst approach is being developed by Questor. Their system consists of a small volume thermal reactor bolted onto the cylinder head, in which partial oxidation of engine HC and CO emissions occurs. This is followed by an Inconel 601 screen $NO_x$ reduction catalyst, which is followed by a final oxidizing thermal

Table 11 **Durability Data for Thermal Reactor Systems**

| Reactor | Mileage | Emissions g/mi<br>HC | <br>CO | <br>$NO_x$ |
|---|---|---|---|---|
| duPont[a] | 20,591[b] | 1.0 | 22 | 3.2 |
| Ford (IIEC)[a] | 63,000[b] | 0.54 | 16 | 0.96 |
| Ethyl[c] | 50,000 | 1.1 | 7.9 | 1.6 |

[a] Rich reactor system.

[b] Emissions measured with Federal 7-mode test procedure. Numbers shown are twice-measured values that correspond approximately to 1975 CVS-CH Test.

[c] Lean reactor system.

Table 12 Emissions Data for Reactor-Converter Systems

| System | Mileage | Test | Emissions g/mi[a] HC | CO | $NO_x$ |
|---|---|---|---|---|---|
| GM Triple Mode[b] | low | GM 4-test avg. | 0.25 | 2.4 | 0.34 |
|  | low | EPA 3-test avg. | 0.21 | 1.7 | 0.47 |
| Questor[c] | 4,000 | EPA | 0.15 | 2.3 | 0.37 |
|  | 8,000 | EPA 2-test avg. | 0.12 | 2.3 | 0.33 |
|  | 19,000 | Questor | 0.59 | 3.3 | 0.38 |
|  | 19,000 | Questor[d] | 0.21 | 2.0 | 0.38 |

[a] 1975 CVS-CH test procedure.

[b] Reactor mode does not operate during CVS-CH test, 5000 lb car. Data received up to October 1972.

[c] 5,000-lb car, 400-CID engine. Data received up to January 1973.

[d] Air pump replaced and test rerun.

reactor. Air is injected into the exhaust ports and downstream of the $NO_x$ catalyst. The engine is operated fuel-rich to reduce engine $NO_x$ emissions so there is a fuel economy penalty relative to the 1971 production test vehicle of about 25 percent.

Emissions below the 1976 standards have been achieved and the durability is promising as shown by the emissions data in Table 12. The major disadvantages of this system are its substantial fuel economy penalty and its complexity. The catalyst is operated at sufficiently high temperatures (about 1750°F) to be insensitive to catalyst poisons such as lead in the fuel. However, as a consequence, a catalyst protection system where water-ethylene glycol mixture is injected into the catalyst bed to prevent over-temperature is required. The adequacy of this type of control system in the hands of the public needs to be carefully examined. Also, since the fuel-air mixture is leaned out at speeds above those encountered in the CVS test procedure to improve fuel economy, $NO_x$ emissions rise.

Serious consideration should be given to the general question of how much emission control systems can be modified to improve vehicle performance at conditions not encountered in the CVS test when such modification results in reduced emissions control.

## 7. Wankel Rotating Combustion Engines

There is much interest in the Wankel rotary engine since it has the potential of being a small, relatively low-cost power plant. It is a relative newcomer to the field of prime movers. Though Felix Wankel, the man credited with its invention, has spent virtually a lifetime working on the concept, the engine only came into prominence in the mid- to late-1950's. Most of the effort spent on the engine to date has been directed toward improving durability and performance. Only recently has there been any significant attempt to investigate the exhaust-emission characteristics.

The most prominent advantages of the RC engine are its high specific output, its fewer number of parts (approximately 40 percent less than a conventional reciprocating engine), and its smoother operation. Its disadvantages include the higher centerline crankshaft, the complex geometry of its seals (apex and side), their durability, the complex housing shape, and high fuel consumption. Engine compactness is an advantage in packaging the emission control system, low engine cost helps to compensate for the increased cost of the emission control system and controls.

Emissions from the Wankel engine itself depend on the design details of the engine and the operating air-fuel ratio. At the present state of development of the engine, carbon monoxide (CO) is about the same to slightly higher (1-3 times), hydrocarbons (HC) much higher (2-5 times), and the oxides of nitrogen ($NO_x$) significantly lower (1/4-3/4) than comparable uncontrolled reciprocating engines. The Wankel engine has a distinct $NO_x$ emission advantage over conventional reciprocating engines. However, its hydrocarbon emission control problem is more difficult.

Another often-stated advantage of Wankel engines is that their exhaust-gas temperature is higher than in a piston engine. This, coupled with the compact geometry and nearly continuous rather than intermittent flow from the exhaust port, makes them suited to a thermal-reactor emission control system. The higher exhaust gas temperature is also an advantage during the cold-start portion of the Federal test cycle because the emission controls warm up more rapidly.

The fuel consumption of current production Toyo Kogyo Wankel engine powered compact vehicles is at least 25 percent above that of a comparable reciprocating engine vehicle. This fuel penalty results from the richer carburetor calibration used to achieve emission control to the 1973 Federal levels, from the different combustion characteristics of the engine, from gas leakage past the seals, and from higher heat losses.

The different emission characteristics of the Wankel engine result from the differences in the combustion process and engine geometry between it and conventional engines. One difference is thought to be a charge stratification that occurs in the Wankel engine. As the rotor accelerates the intake charge, the heavier fuel droplets tend to lag behind and form a fuel-rich region near the trailing end of the combustion chamber. The combination of varying fuel-air ratio and higher heat transfer to the combustion chamber walls as well as seal leakage are thought to contribute to lower $NO_x$ emissions. One consequence of the charge stratification is that the engine $NO_x$ emissions are less sensitive to changes in the overall fuel-air ratio as shown in Figure 7.

The Wankel engine combustion also has disadvantages. The engine has a high surface-to-volume ratio; thus the HC quench and crevice volumes are larger than in a piston engine. Unburned mixture blows by the apex seals into the exhausting chamber. All these factors contribute to the higher HC emissions. The higher heat transfer due to higher surface-to-volume ratio and seal leakage reduce the thermal

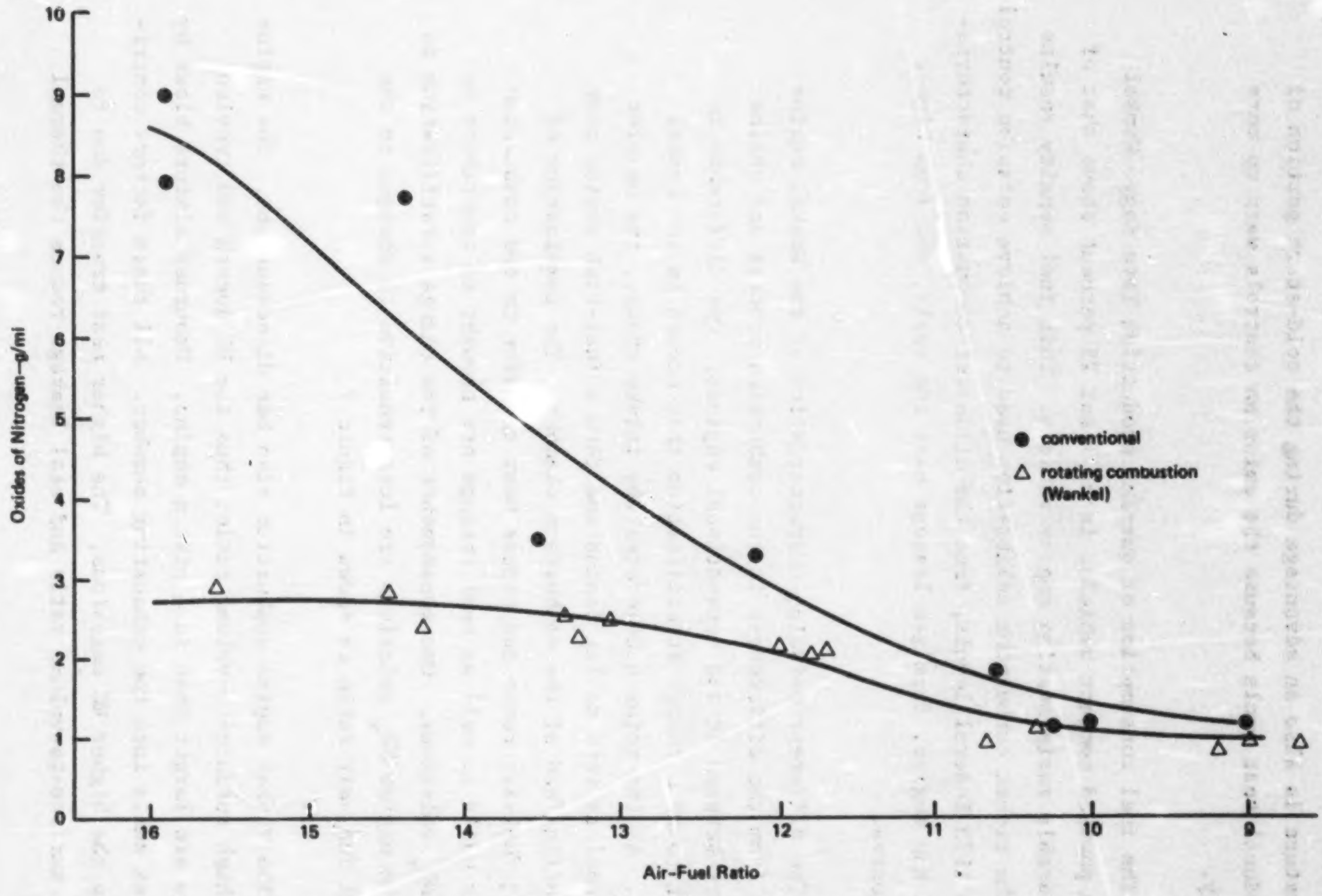


FIGURE 7 Effect of air-fuel ratio on $NO_x$ emissions for a Wankel and a conventional spark-ignition engine at constant loads.

efficiency of the engine.

Like the piston engine, the Wankel engine will require external emission-control devices to approach the 1975-76 standards. As a consequence of the higher exhaust-gas temperature and layout of the engine, a thermal-reactor type of control system operates better on a Wankel than a piston engine. This by no means implies that a catalytic converter or a combination thermal reactor-catalytic converter cannot be used.

Table 13 lists the best emission levels obtained by different manufacturers with thermal reactor Wankel-engine systems. The data were obtained in a compact 2750-lb vehicle. The durability of the rich thermal reactor system below the 1975 emission levels has been demonstrated by Toyo Kogyo, with one car successfully tested to 50,000 miles and with one car still under test at 28,000 miles. The reactor core temperature is held below 1650°F and 50,000-mile deterioration factors were 1.14 for HC, less than 1 for CO, and 1.05 for $NO_x$. The CVS test fuel economy of the Toyo Kogyo vehicle is about 30 percent worse than that of an equivalent weight piston-engine car.

The low engine $NO_x$ level of the Wankel engine is attractive since it may be possible to achieve the 1976 standards with a thermal reactor and EGR alone. It has been shown that the addition of EGR and a richer carburetor setting does reduce the $NO_x$ emissions from the thermal reactor rotary engine system, but it is not clear that $NO_x$ emissions can be reduced below 0.4 g/mi while retaining adequate driveability.

The effect of EGR on $NO_x$ emissions from the Wankel engine (without a thermal reactor or catalyst) is shown in Table 14. At leaner air-fuel ratios than those required for successful operation of the rich thermal reactor system, EGR is more effective at reducing $NO_x$ emissions. However, the HC and CO emissions are high, and effective oxidation catalyst systems and cold-start engine emission controls

Table 13 Best Emissions Results, Thermal Reactor and Wankel Engine 2750-lb Compact Car

| Manufacturer | System[a] | Mileage | No. of Tests | Emissions in g/mi[b] | | | CVS Fuel Economy, |
|---|---|---|---|---|---|---|---|
| | | | | HC | CO | $NO_x$ | mpg[c] |
| Toyo Kogyo[d] | Reactor | 4,000 | Many | 0.32 | 3.1 | 0.83 | 12.1 |
| | | 50,000 | 3 | 0.36 | 2.6 | 0.87 | |
| | Reactor + EGR | low | 8 | 0.35 | 2.2 | 0.49 | 11.2 |
| General Motors | Reactor | low | 72 | 0.60 | 5.0 | 0.60 | |
| | (best effort) | low | 1 | 0.43 | 2.8 | 0.44 | |

[a] All these systems are carbureted fuel-rich (about 12:1).

[b] 1975 CVS-CH test procedure. Data received up to October 1972.

[c] CVS-CH test procedure; 1973 equivalent vehicle, 12.7 mpg.

[d] RX3 35-CID x 2-rotor engine, manual 4-speed transmission.

Table 14 Effect of EGR on Wankel Bare Engine $NO_x$ Emissions[a]

| Condition | Emissions in g/mi[b] | | | Driveability |
|---|---|---|---|---|
| | HC | CO | $NO_x$ | |
| Baseline Engine | 19 | 50 | 2.5 | Production |
| Driveability limited EGR | 19 | 50 | 1.4 | Poor |
| Richer carburetor setting + EGR | 20 | 65 | 0.75 | Acceptable |
| Leaner carburetor improved induction system, EGR | 19 | 55 | 0.3 | Acceptable |

[a] General Motors data at low mileage, 2750-lb car.

[b] 1975 CVS-CH test procedure. Data received August 1972.

would be required to bring the levels of all three pollutants below the 1976 standards. A major unknown is the effect of EGR on the driveability of the Wankel engine powered vehicle. The data obtained from the manufacturers were conflicting. For example, Toyo Kogyo furnished data shown in Figure 8, which indicate that the 1976 $NO_x$ level cannot be reached with acceptable driveability at any fuel economy penalty.

The best results achieved with oxidation catalysts and rotary engines are shown in Table 15. Levels approaching the 1975 standards for HC and CO have been achieved at low mileage with a compact car.

In summary, current production rotary engines in compact cars operated with rich carburetor settings and thermal reactors have been developed to meet the 1975 standards with $NO_x$ levels of about 1 g/mi. The durability of this system is promising. However, the fuel economy penalty of this system compared with a current equivalent piston engine is about 30 percent. The use of EGR and richer carburetion with the thermal reactor reduces $NO_x$ emission levels, but not yet below 0.4 g/mi with adequate driveability. The fuel economy penalty increases by an additional 5 percent.

Other control approaches with the Wankel engine have been less extensively developed. At leaner carburetor settings, oxidation catalysts have been shown to reduce HC emissions at low mileage in a compact car to levels about 50 percent above the 1975 standard and CO to well below the standard. However, the durability of the Wankel engine catalyst control system has not been evaluated. EGR has been shown to reduce $NO_x$ levels below 0.4 g/mi, but engine HC and CO emissions were comparable to uncontrolled piston engine levels.

Preliminary data on a Wankel engine with a thermal reactor, $NO_x$ reduction catalyst, and HC/CO oxidation catalyst in a compact vehicle at low mileage indicate $NO_x$ levels below 0.4 g/mi can be obtained. This system is complicated and would be expected to encoun-

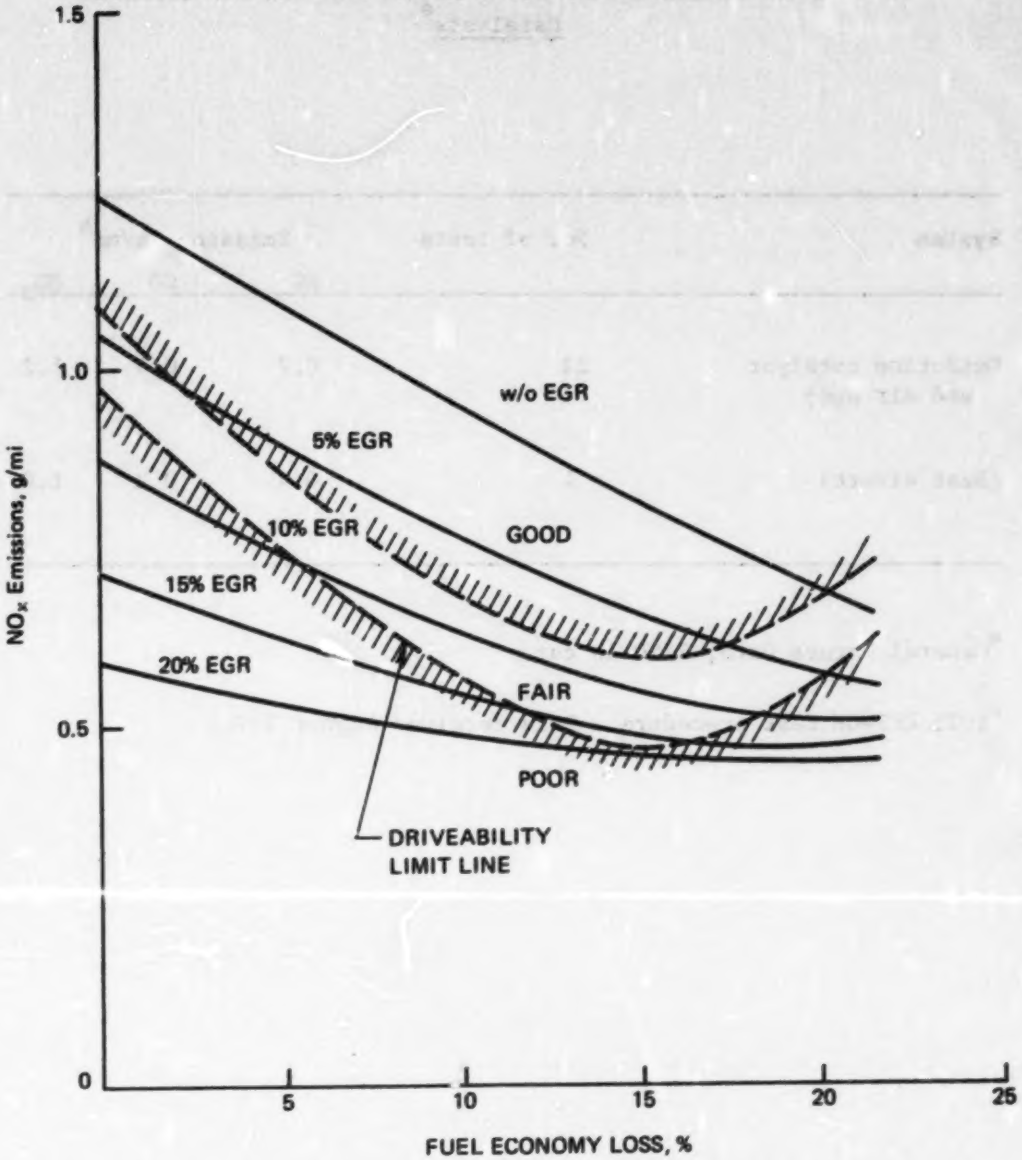


FIGURE 8 Fuel economy loss at various $NO_x$ levels for a range of EGR percentages and air-fuel ratios for a Toyo Kogyo Wankel engine.

Table 15 **Emissions at Low Mileage, Rotary Engine with Oxidation Catalysts**[a]

| System | No. of tests | Emissions g/mi[b] | | |
|---|---|---|---|---|
| | | HC | CO | $NO_x$ |
| Oxidation catalyst and air pump | 22 | 0.7 | 0.4 | 1.2 |
| (Best effort) | 1 | 0.4 | 0.2 | 1.0 |

[a] General Motors data, 2750-lb car.

[b] 1975 CVS-CH test procedure. Data received August 1972.

ter all the durability problems of the dual-catalyst systems for conventional engines.

## 8. Stratified-Charge and Dilute-Combustion Engines

Research and development efforts over several decades have resulted in a number of unconventional piston engine design concepts that appear to have potential for reduced exhaust emissions. These engines fall into two broad categories. First, a number of engine designs, usually called stratified-charge engines, permit operation with overall fuel-air mixtures significantly leaner than chemically correct. As a result, oxidation of carbon monoxide and hydrocarbons is promoted, and decreased mean combustion temperatures tend to limit the formation of oxides of nitrogen. In a second class of engines, combustion chamber design is such as to permit significant dilution of the fuel-air charge with inert exhaust gases, thereby reducing combustion temperatures and oxides of nitrogen. This is usually achieved by increasing combustion chamber turbulence before and during combustion either through control of inlet valve passage area or through generation of air swirl within the cylinder by means of inlet port orientation.

In contrast to such alternative vehicle power plants as gas turbines or Rankine cycle engines, these unconventional reciprocating engines offer the advantage that minimal changes from current basic production techniques would be required. Additionally, several of these designs exhibit excellent fuel economy relative to conventional engines. The stratified-charge concept can be applied to the rotary engine as well.

Three of these concepts have been developed to the stage where emission tests of engines in passenger vehicles have been carried out. Honda has developed the concept of a three-valve, dual-carburetor, divided-chamber stratified-charge engine into a low-emissions engine design called the Compound Vortex Controlled Combustion (CVCC) system. Honda has extensive development and design experience with their CVCC engine in their own compact cars, and has built and tested CVCC engines of appropriate size in General Motors Vega and Impala vehicles. Honda has announced plans to mass-produce vehicles with their CVCC engine by 1975.

Ford has developed several engines using its open chamber cylinder fuel-injection stratified-charge engine concept (PROCO). These engines have been tested in vehicles and results show promising emissions and fuel economy. Ford has also tested a carbureted high-turbulence, dilute-combustion engine with similar piston and cylinder head geometry to the PROCO engine.

The achievements of these different engine concepts to date and their potential will now be reviewed.

## Open-Chamber Stratified Charge Engines

Recently, research and development on the open-chamber stratified charge engine has been sponsored by the U.S. Army Tank-Automotive Command (TACOM). This work has involved development and testing of two engine designs, one based on the Ford Programmed Combustion Process (PROCO) and the other based on the Texaco Controlled Combustion Process (TCCP). The development of a jeep engine for the Army has been undertaken by Ford and Texaco, respectively, on a contract basis. Ford has been conducting its own program to develop passenger vehicle engines.

Both the Ford and Texaco engines employ a combination of air inlet port swirl and high-pressure, timed, combustion-chamber fuel-injection to achieve a local fuel-rich ignitable mixture near the spark plug while the overall fuel-air ratio supplied to the engine is fuel-lean for most operating conditions. Figure 9 shows the geometry of the Ford engine. Engines based on these combustion chamber designs yield quite low carbon monoxide emissions. While hydrocarbon and nitric oxide emissions are below those of conventional engines,

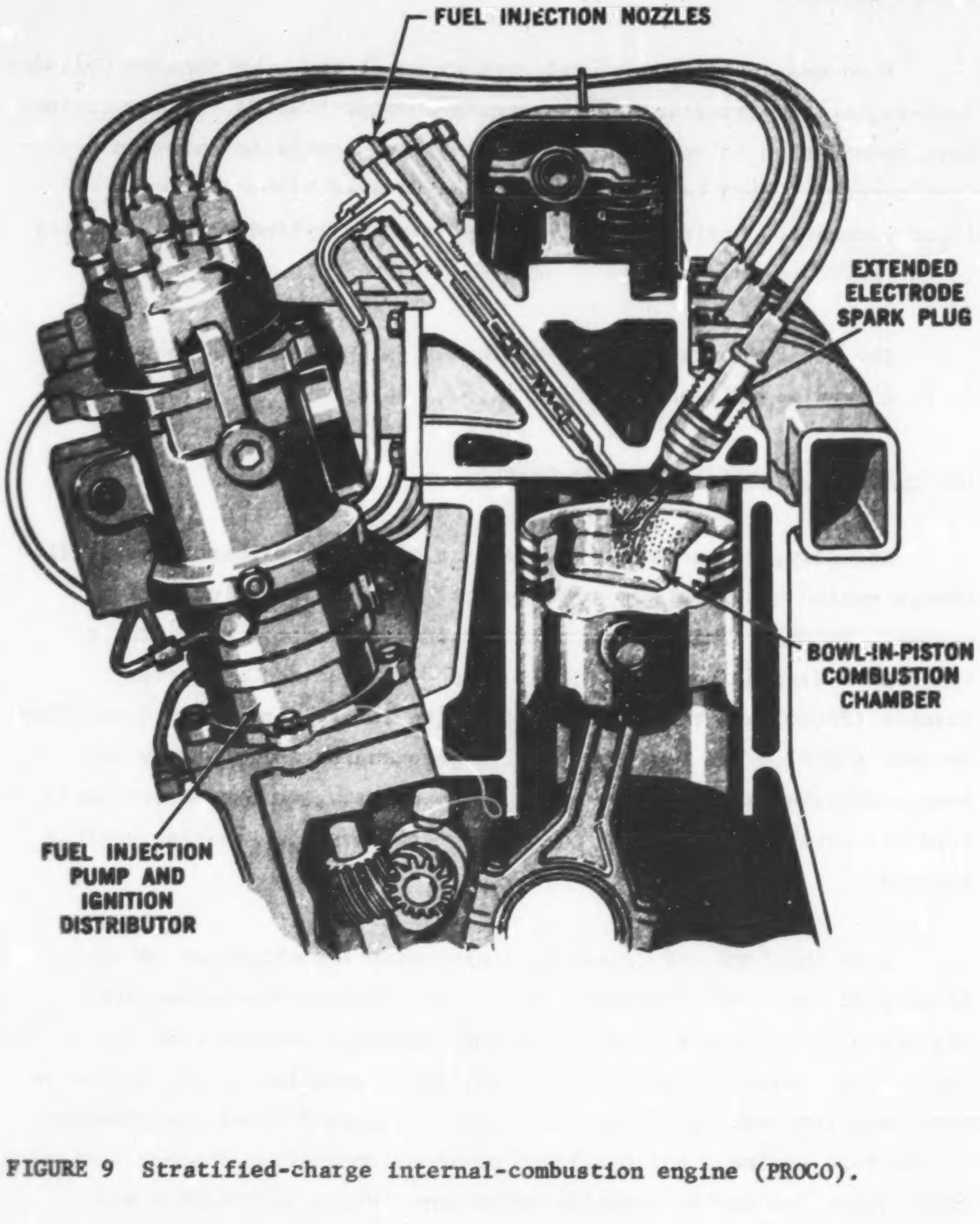

FUEL INJECTION NOZZLES
EXTENDED ELECTRODE SPARK PLUG
BOWL-IN-PISTON COMBUSTION CHAMBER
FUEL INJECTION PUMP AND IGNITION DISTRIBUTOR

FIGURE 9 Stratified-charge internal-combustion engine (PROCO).

additional control techniques are required to meet the 1976 federal standards. The present TACOM vehicles employ exhaust gas recirculation for $NO_x$ control and oxidizing catalysts for control of carbon monoxide and particularly unburned hydrocarbons. As a consequence, the usual problems with oxidizing catalyst durability have been experienced.

Military vehicles equipped with four-cylinder 70 HP L-141 engines modified both by Ford and by Texaco are currently undergoing emissions durability tests. Emissions levels for these vehicles, which are equipped with oxidizing catalysts and exhaust gas recirculation, are presented in Table 16 for the Ford and Texaco vehicles. Results indicate that with low vehicle mileage these systems are capable of meeting the 1976 Federal emissions standards, and that durability is promising.

The most important conclusion from these durability tests is that the basic combustion process is stable. Difficulties with plugging of EGR systems with particulates were experienced during this mileage accumulation. The major durability problem is the oxidation catalyst. The Ford engine required two catalyst changes and frequent maintenance. The Texaco engine used three oxidation catalysts in series to achieve the required HC and CO emission control.

In addition to work performed under contract for TACOM, Ford has conducted experiments involving consumer-type vehicles. Both four-cylinder and eight-cylinder engine conversions have been used. Stratified-charge engine installations have also been made on two commercial-type vehicles. Emissions measurement results are presented in Table 17. It is evident from Table 17 that three of the four vehicles under test in this program are capable of meeting the 1976 Federal emission standards at low vehicle mileage. These vehicles are currently undergoing mileage accumulation procedures.

One of the advantages of the stratified-charge engine is

Table 16 **Emissions from Military Jeep with Stratified-Charge Engine**[a]

| Engine | Mileage | CVS Fuel Economy, mpg[b] | Emissions g/mi[c] | | |
|---|---|---|---|---|---|
| | | | HC | CO | $NO_x$ |
| L - 141 Ford PROCO | low | 18.5 - 23 | 0.37 | 0.93 | 0.33 |
| | 17,123[d] | | 0.64 | 0.46 | 0.38 |
| L - 141 Texaco TCP[e] | low | 16 - 22 | 0.37 | 0.23 | 0.31 |
| | 10,000 | | 0.77 | 1.90 | 0.38 |

[a] Emission controls include oxidation catalyst, EGR, throttling at light load.

[b] Fuel economy varies test to test because of changes in EGR and exhaust back pressure.

[c] 1975 CVS-CH test procedure. Data received August 1972.

[d] Vehicle required two oxidation catalyst changes during the 17,123-mileage durability testing.

[e] Three oxidation catalysts in series used to achieve low HC and CO emissions.

Table 17 Low-Mileage Emission Levels for PROCO Conversion

| | CVS-CH Test, g/mi | | | CVS Fuel Economy, mi/gallon | Inertia Test weight, lb | No. of Tests |
|---|---|---|---|---|---|---|
| | HC | CO | $NO_x$ | | | |
| PROCO 141-CID Capris | 0.12 | 0.46 | 0.32 | 20.4 | 2500 | 6 |
| | 0.13 | 0.18 | 0.33 | 25.1 | - | - |
| | 0.11 | 0.27 | 0.32 | 22.3 | 2500 | - |
| PROCO 351-CID Torino | 0.30 | 0.37 | 0.37 | 14.4 | 4500 | 5 |
| PROCO 351-CID Montegos | 0.36 | 0.13 | 0.63 | - | - | - |
| | 0.33 | 1.08 | 0.39 | 12.8 | - | - |
| M-151 PROCO ¼-ton Truck | 0.12 | 0.30 | 0.34 | 20.2 | 3000 | 4 |
| ¼-ton PROCO Mail Truck | 0.18 | 0.21 | 0.51 | 22.9 | 2500 | 9 |

Note: Figures are averages for number of tests shown. All vehicles used EGR and noble-metal catalysts. Data received up to October 1972.

## Table 17(b) EXPERIMENTAL FORD PROCO VEHICLES

### 1. 141-CID PROCO Engine/Capri Vehicle

A. L-141 four-cylinder PROCO engine.
B. PROCO fuel injection system.
C. Fixed orifice EGR system with 20-25% EGR rate and EGR to water heat exchanger.
D. Low thermal inertia exhaust manifold.
E. Engelhard PTX-5D catalysts, 5-inch diameter, 6 inches long.
F. Four-speed manual transmission.

### 2. 351-CID PROCO/Torino Vehicle

A. 351 V-8 PROCO engine.
B. PROCO fuel injection system.
C. Fixed orifice EGR system with 22-27% EGR rate and EGR to water heat exchanger.
D. Low thermal inertia exhaust manifolds.
E. Engelhard PTX-5D catalysts, 5-inch diameter, 6 inches long on 12 corrugations-per-inch support, one on each bank.
F. Control system to close EGR and retard injection timing for the first 50 seconds of the test.
G. Three-speed automatic transmission.

### 3. 141-CID PROCO Engine in 1/4-Ton Military Truck

A. L-141 four-cylinder PROCO engine.
B. PROCO fuel injection system.
C. Fixed orifice EGR system with 20-25% EGR rate and EGR to water heat exchange.
D. Low thermal inertia exhaust manifold.
E. Matthey-Bishop noble metal catalyst, 5-inch diameter, 6 inches long on eight corrugations-per-inch support.
F. Control system adjusted to prevent EGR closing and fuel enrichment at maximum accelerator pedal position (derated setting).

### 4. 141-CID PROCO Engine in 1/4-Ton Mail Truck

A. L-141 PROCO engine.
B. PROCO fuel injection system.
C. Fixed orifice EGR system with 20-25% EGR rate and EGR to water heat exchanger.
D. Low thermal inertia exhaust manifold.
E. Engelhard PTX-5D catalyst, 5-inch diameter, 6 inches long on eight corrugations-per-inch support.
F. Two speed automatic transmission.
G. Control system adjusted to prevent EGR closing and fuel enrichment at maximum accelerator pedal position (derated setting).

excellent fuel economy relative to conventional engines, particularly when emissions controls are applied. Table 17 gives fuel economy data obtained during the CVS test. The miles per gallon figures are substantially better (about 25 percent) than values for dual-catalyst conventional-engine systems.

Additional data with the TACOM military jeep show that fuel economy is still dependent on level of $NO_x$ emissions. The original version of the stratified charge L-141 engine developed for optimum fuel economy showed a 30 percent fuel economy gain over the conventional carbureted jeep engine. However, as in a conventional engine, when EGR is used to reduce $NO_x$ emissions the fuel economy is reduced. With $NO_x$ emissions at 0.33 g/mi, the emission-controlled stratified-charge engine fuel economy is comparable to that of the original L-141 conventional engine. With less EGR, at 0.7 g/mi $NO_x$, about a 10 percent fuel economy gain is obtained.

### Divided Combustion Chamber Engines: Fuel Injected

In a number of designs, charge stratification is achieved by dividing the combustion region into two adjacent chambers. Two quite different categories of divided chamber engines exist. First, a design that traditionally has been known as a prechamber engine employs a small auxiliary or ignition chamber that communicates with the main combustion chamber, which comprises the region above the piston. In the prechamber engine, the prechamber volume is typically 5 percent of the total combustion chamber volume. In operation, a small quantity of ignitable fuel-rich mixture is supplied to the prechamber while a very lean mixture is supplied to the large main combustion chamber above the piston. The flame expanding from the point of ignition within the prechamber then serves to ignite the ordinarily unignitable main chamber fuel-air mixture. The Honda Compound Vortex Controlled Combustion (CVCC) engine is a carbureted engine of this type and is discussed subsequently.

A second type of divided combustion chamber engine employs a two-stage combustion process resulting from division of the combustion region into two chambers of approximately equal volume. One chamber, the secondary chamber, comprises the space immediately above the top of the piston while the other chamber, usually referred to as the primary chamber, is separated from the secondary chamber by a dividing orifice. In operating this type of engine, fuel is supplied only to the primary combustion chamber such that at the beginning of the combustion process the primary chamber contains an ignitable fuel-air mixture while the secondary chamber, the chamber adjacent to the piston top, contains only air. Following ignition of the primary chamber mixture, high-temperature fuel-rich combustion products expand rapidly into the cool air contained in the secondary chamber, and, as a consequence of the resulting quenching action, the formation of nitric oxide is suppressed. In addition, the presence of excess air in the secondary chamber tends to promote complete oxidation of hydrocarbons and carbon monoxide.

Results of limited research conducted both by university laboratories and by several vehicle manufacturers indicate that reduction of oxides of nitrogen of as much as 80-90 percent relative to conventional engines can be achieved with this type of combustion chamber. While hydrocarbon and carbon monoxide levels are substantially lower than those of conventional engines, it appears that further work with combustion chamber geometries and fuel-injection system designs will be necessary to fully evaluate the potential for reduction of these emissions.

Ford has obtained emissions results with a one-cylinder laboratory engine equipped with a divided combustion chamber. These results are presented in Table 18. For purposes of comparison, results for a single-cylinder PROCO engine operated under similar conditions are also presented. In the case of the PROCO engine, $NO_x$ control is achieved by exhaust-gas recirculation. It is evident from

Table 18 Single-Cylinder Engine Performance and Emissions

(All Data at 1500 rpm - 40 psi imep)

| Engine | Fuel Introd. Method | $NO_x$ Red. Method | Gas-Fuel Ratio | g/ihp-hr | | Indicated Specific Fuel Consumption lb/ihp-hr |
|---|---|---|---|---|---|---|
| | | | | HC | CO | |
| $NO_x$ = 1.0 g/ihp-hr | | | | | | |
| PROCO | Fuel injection | EGR | 19.9 | 3.0 | 13.0 | 0.377 |
| Divided Chamber | Fuel injection | none | 27.0 | 0.4 | 2.5 | 0.378 |
| $NO_x$ = 0.5 g/ihp-hr | | | | | | |
| PROCO | Fuel injection | EGR | 20.9 | 4.0 | 14.0 | 0.383 |
| Divided chamber | Fuel injection | none | 28.3 | 0.75 | 3.3 | 0.377 |

Data received up to October 1972.

the data in Table 18 that for a given level of $NO_x$ control, the divided chamber engine and the PROCO stratified-charge engine are roughly equivalent in fuel economy. Further, the divided chamber engine appears to emit lesser quantities of carbon monoxide and unburned hydrocarbons. In the case of the divided-chamber results in Table 18, $NO_x$ control results from basic design of the engine. Exhaust gas recirculation is not employed.

## The Honda Compound Vortex Controlled Combustion (CVCC) Engine

An alternative approach achieves charge stratification with a small prechamber and a dual-carburetor three-valve system. While this concept is not new, its low emissions potential has only recently been realized in practice in vehicles by Honda with their CVCC system. The additional Honda developments appear to be the optimization of air-fuel ratio variation in the dual-carburetor system, and the design of the main combustion chamber to achieve a slow burn. Figure 10 shows the geometry of the Honda engine. The engine block, pistons, and spark plugs are conventional; only the cylinder head, intake and exhaust manifolds, and carburetor are modified. The cylinder head contains a small precombustion chamber in addition to the main combustion chamber. The spark plug is located in the prechamber, which is fed through a separate carburetor and intake system with a fuel-rich mixture through a small third valve. The main carburetor and intake system feeds a fuel-lean mixture to the normal intake valve in the main combustion chamber.

The fuel-rich mixture ensures good ignition, the approximately stoichiometric mixture at the prechamber exit propagates the flame into the fuel-lean mixture in the main chamber. The main combustion chamber is designed to control the rate of flame spreading; a slow-burning flame is required to reduce $NO_x$ formation and allow HC and CO burnup inside the engine. $NO_x$, CO, and HC emissions are all lower than a conventional engine at the same lean air-fuel ratios.

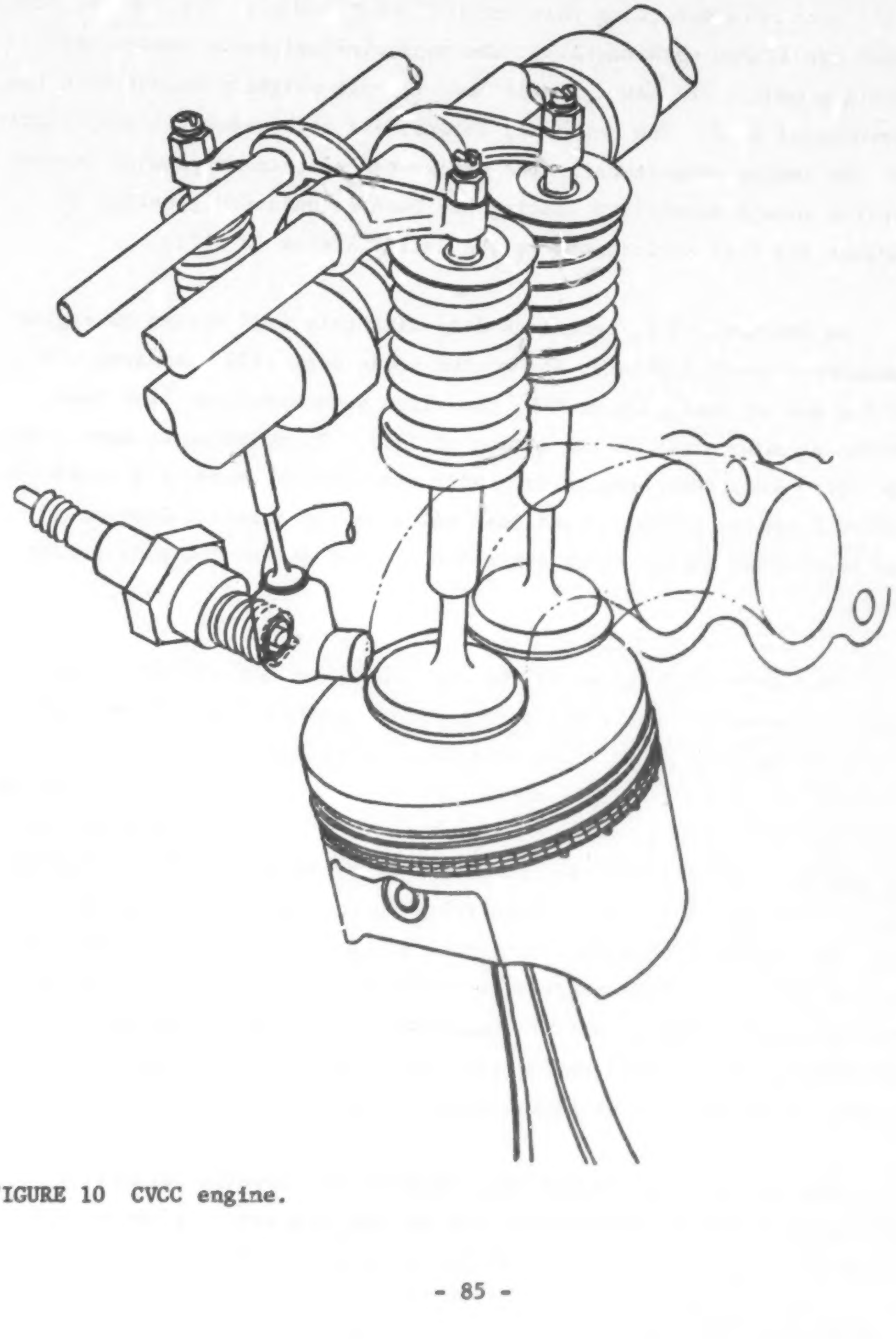


FIGURE 10 CVCC engine.

The emissions are not especially sensitive to variations in air-fuel ratio. Thus the required performance of the double carburetor system is not much more demanding than current requirements. The two throttle plates are linked mechanically. The mean air-fuel ratio varies with operating mode. The new cylinder head is only slightly higher than the conventional head. The new head, intake, and carburetor fit comfortably into the engine compartment. The engine can operate on regular leaded gasoline though durability testing has been on unleaded gasoline to simulate the fuel anticipated in the United States in 1975.

In February 1971, emissions data with this CVCC system on engine dynamometer tests indicated the engine could meet 1975 standards without the use of catalysts or EGR; the first successful car test that met the standards was in the spring of 1972. In addition to developing a 2-liter, 4-cylinder engine for their own vehicle, Honda has developed a 140-CID engine cylinder head that bolts on the standard Chevrolet Vega 4-cylinder engine block and a 350 CID V-8 engine for a Chevrolet Impala.

The Honda CVCC system is the most developed stratified charge engine to date, and has the lowest engine emissions. Emissions data at low mileage for Honda Civic vehicles and the modified GM vehicles are shown in Table 19. This emission control is inherent in the engine, and there is no EGR or catalytic converter. Both the 2-liter car and the modified GM vehicles meet the 1975 levels at low mileage. The CVS fuel economy is also shown. Especially impressive is the standard deviation of the low mileage emissions of the 25 vehicles in the first line of Table 19. The standard deviation is 10 to 15 percent of the mean emissions. These cars are hand-made production prototypes. In comparison, conventional engine vehicles show standard deviations of 30 percent of the mean at higher emission levels.

One car (a Honda Civic) has completed 50,000-mile durability testing on a chassis dynamometer and met the standards at every test

Table 19 Low-Mileage Emissions Data from Honda Tests of 1975 CVCC Systems

| Vehicle | Engine | Mileage | No. of Vehicles | Inertia Weight, lb | Emissions g/mi[a] |  |  | CVS Fuel Economy, mpg |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | HC | CO | $NO_x$ |  |
| Honda Civic manual trans. | 2 liter CVCC | low | 25 | 2000 | 0.23 | 2.4 | 0.95 | 22 |
| Honda Civic manual trans. | 2 liter CVCC[b] | low | 25 | 2000 | 0.21 | 2.3 | 0.75 |  |
| Honda Civic auto trans. | 2 liter CVCC | low | 3 | 2000 | 0.23 | 2.6 | 1.15 | 21 |
| GM Vega manual trans. | 140 CID GM | low | 1 | 2500 | 2.13 | 10.6 | 3.8 | 17.2[c] |
| GM Vega manual trans. | 140 CID CVCC | low | 1[d] | 2500 | 0.26 | 2.6 | 1.2 | 18.6 |
| GM Impala | 350 CID CVCC | low | 1[d] | 4500 | 0.25 | 3.0 | 1.23 | 11 |

[a] 1975 CVS-CH test procedure. Data received up to April 1973.

[b] CVCC system with improved manifold and carburetor.

[c] 1972 CVS-C test procedure.

[d] Two-test average.

throughout the 50,000 miles. The maintenance carried out corresponded approximately to an engine tune-up every 12,000 miles. Three other vehicles have been tested over extended mileage on the road (32,019 to 44,033 miles) before engine modifications were made. Emissions data and actual or estimated 50,000-mile deterioration factors are shown in Table 20. The deterioration factors are comparable to values obtained with current conventional engines.

Development of the Honda CVCC engine to achieve lower $NO_x$ emissions is continuing. The effects of modifications in cylinder head and prechamber geometry, fuel-air ratio control, combustion duration, and EGR are being examined. Table 21 shows the current state of progress in meeting the 1976 standards. At low mileage, a Honda Civic car with manual transmission and an improved engine without EGR showed about a factor of two reduction in $NO_x$ compared to the cars represented in Table 19. Equivalent HC and CO control has been retained. With EGR a further reduction in $NO_x$ is obtained, but HC and CO emissions rise. The fuel economy also deteriorates as the CVCC system is modified for lower $NO_x$.

These data suggest that HC and CO emissions can be brought below 1975 levels with the Honda CVCC engine, but that $NO_x$ levels for modest performance and fuel economy penalties are between about 0.8 and 1.3 g/mi depending on vehicle and engine size. The fuel economy penalty increased substantially when the CVCC engine in a Honda CIVIC was modified to meet the 1976 standards.

This engine concept appears to have lower basic engine emissions than any other spark-ignition engine concept under development. It is not yet close to the stage of meeting the 1976 standards in a standard-sized car.

## Dilute Combustion Engines

A well-known technique for control of $NO_x$ emissions from conven-

Table 20 **Durability Data from Honda Tests of 1975 CVCC Systems**[a]

| | | Emissions, g/mi[b] | | | 50,000-Mile Deterioration Factors[c] | | |
|---|---|---|---|---|---|---|---|
| Vehicle | Mileage | HC | CO | $NO_x$ | HC | CO | $NO_x$ |
| 1006 | 4,000 | 0.22 | 2.4 | 0.96 | | | |
| | 50,000 | 0.26 | 2.6 | 0.99 | 1.16 | 1.07 | 1.03 |
| 2033 | 4,000 | 0.21 | 2.6 | 0.87 | | | |
| | 40,003 | 0.24 | 2.6 | 0.93 | | | |
| | 50,000[d] | 0.25 | 2.7 | 0.90 | 1.15 | 1.08 | 1.04 |
| 2034 | 4,000 | 0.24 | 2.4 | 0.83 | | | |
| | 44,033 | 0.28 | 2.6 | 0.82 | | | |
| | 50,000[e] | 0.25 | 2.6 | 0.82 | 1.06 | 1.05 | 1.0 |
| 2035 | 4,000 | 0.21 | 2.4 | 0.96 | | | |
| | 32,019 | 0.26 | 3.0 | 1.0 | | | |
| | 50,000[f] | 0.24 | 2.7 | 0.96 | 1.12 | 1.12 | 1.0 |

[a] Honda Civic Vehicle, 2-liter engine, 2000-lb inertia weight.

[b] Interpolated values from 1975 CVS-CH test data taken every 4000 miles. Data received up to April 1973.

[c] Emissions at 50,000 miles/emissions at 4000 miles.

[d] Extrapolated, maximum mileage before engine modifications 40,003.

[e] Extrapolated, maximum mileage before engine modifications 44,033.

[f] Extrapolated, maximum mileage before engine modifications 32,019.

Table 21 Low-Mileage Emission Data from CVCC System Developed for Low $NO_x$

| | Emissions, g/mi[a] | | | CVS Fuel Economy, mpg |
|---|---|---|---|---|
| | HC | CO | $NO_x$ | |
| 1975 CVCC system, 25-car average[b] | 0.23 | 2.41 | 0.95 | 22 |
| Improved CVCC system with 1 car, three-test average[b] | 0.25 | 2.5 | 0.43 | |
| Improved CVCC system with EGR, 1 car, one test[c] | 0.28 | 3.1 | 0.24 | 18.1 |

[a] 1975 CVS-CH test procedure. Data received up to April 1973.

[b] Honda Civic vehicle, 2000 lb inertia weight, 2-liter engine, manual transmission. No EGR or catalytic converter.

[c] Same as b, but with EGR.

tional engines is recirculation of exhaust gases to the incoming fuel-air mixture. Such dilution of the inlet charge reduces peak combustion temperatures and therefore suppresses the formation of nitric oxide. Major problems encountered with exhaust gas recirculation have been poor driveability because of erratic combustion and also loss of fuel economy partly because of reduced flame speeds.

A number of engines designed to overcome the above problems have been based on increased fuel-air mixture turbulence. Increased turbulence has been achieved either through control of inlet valve area when operating under throttled engine conditions or through development of cylinder air swirl by suitable orientation of the inlet port.

Experimental results obtained by Ford Motor Company for a high swirl combustion chamber design using large quantities of exhaust gas recirculation are shown in Table 22. Detailed engine specifications are also given in the table; the engine geometry is similar to the PROCO geometry in Figure 9. It appears that this engine-vehicle system is capable of meeting the 1976 $NO_x$ standard without use of a reducing catalyst. Further, hydrocarbon and carbon monoxide levels have been reduced to below the 1976 standards through use of a noble-metal oxidizing catalyst. These results pertain to low vehicle mileage emissions only.

The high turbulence combustion engine is in a preliminary research stage, and a host of problems must be studied before the potential for successful large-scale production can be estimated.

Table 22 Low-Mileage Emissions: Ford Fast-Burn Engine[a]

| | Emissions, g/mi[b] | | | CVS Fuel Economy, mi/gallon | HC/CO Catalyst Efficiency |
|---|---|---|---|---|---|
| | HC | CO | $NO_x$ | | |
| With HC/CO catalysts | 0.38 | 1.46 | 0.37 | 12.9 | 95 |
| Without HC/CO catalysts | 5.69 | 61.2 | 0.32 | 12.9 | |

[a] Vehicle inertia weight 4500 lb.

[b] 1975 CVS-CH test procedure. Data received up to October 1972.

## Ford High-Turbulence Engine Specifications

351-CID V-8 Engine at 11:1 Compression Ratio

High Swirl Intake Ports

Cup-in-Piston Combustion Chamber

Optimized Carburetor Choke for Cold Start

Carburetor Spacer EGR Introduction with Exhaust Port EGR Pickup; EGR Cooled with an Engine Coolant Heat Exchanger; Staged EGR Control System

EGR Cutout for WOT Operation

Dual Oxidizing PTX-523 Catalysts for Each Side of Engine for HC/CO Control
Secondary Air Injection with WOT Cutoff Control

This engine Currently Requires 95 Octane Unleaded Fuel.

## 9. Vehicle Performance, Driveability and Fuel Economy

While the 1976 emissions standards do not directly regulate vehicle performance, the emission control devices and techniques required to meet these standards have a profound effect on at least three areas of vehicle performance--acceleration capability, fuel economy, and driveability.* The consumer is extremely aware of and sensitive to these characteristics, which affect both his pocketbook and his attitude toward any particular vehicle. Traditionally this area has been one in which customer complaints and warranty returns have been especially prevalent. It is not surprising, then, that manufacturers have registered great concern about the adverse effects of emission-control devices. By the same token, however, the market forces impose considerable inherent motivation for manufacturers to devote great attention to product improvement in these areas.

The comments that follow in this chapter refer primarily to vehicles equipped with the dual catalyst emission control system described in Chapter 6. Only with this system is there enough information available to review the effects of the control system on vehicle performance. These experimental 1976 vehicles have not yet demonstrated the potential for meeting the 1976 standards. Thus any assessment of the likely performance and driveability problems is speculative.

As will be noted later, the concerns registered to the Panel by the manufacturers during the 1971 visits were considerably moderated during the 1972 visits. It will be useful to review the manner in which the emission-control techniques influence performance in understanding the reasons for the lessened concern.

---

*Good driveability is loosely defined as the ability of a vehicle to start, operate, and stop smoothly under all environmental and operating conditions without stalls, surges, hesitations, after-firing, etc.

In general, vehicle acceleration capability is reduced by control measures applied for control of all pollutant species (HC, CO, and $NO_x$); however, $NO_x$ control measures that reduce combustion temperature have the most serious deleterious effects. Reductions in compression ratio to enable use of lower octane gasoline resulted in acceleration penalties as did the minimization of enrichment techniques specifically provided for rapid acceleration capability. In addition, the use of EGR to reduce combustion temperatures and thereby inhibit $NO_x$ production imposes a severe acceleration penalty.

Losses in fuel economy result concurrently with most of these losses in acceleration capability and are aggravated by countermeasures taken to overcome deficiencies in acceleration capability and driveability. Many of the smaller engines have been dropped in the various car lines because performance was no longer adequate. The use of a larger displacement engine results in a fuel economy penalty for both in-city and open highway driving. When EGR is used to control $NO_x$ emissions, the flame speed is reduced and the mixture is usually enriched to retain adequate driveability. Both these effects reduce fuel economy.

There are numerous driveability problems, but one of the most troublesome is the cold-start problem. The quick choke action and subsequent lean mixtures required to minimize HC and CO emissions introduce problems with engine stalls and unsatisfactory drive-away during warm-up. EGR and spark retard cause such problems as lack of response, die-outs, and hesitation on accelerations.

In its 1971 report, this panel concluded that all three areas of vehicle performance discussed above would be adversely affected by the 1975 emission control systems. Information received from manufacturers indicated losses in acceleration capability ranging from a minimum of 5 percent to a maximum of 20 percent over 1971 levels. All manufacturers anticipated losses in driveability--in some cases indicated to be severe. Anticipated increases in fuel consumption ranged from 5 to 15 percent for standard-sized cars up to 20 to 30 percent for small cars, again over 1971 levels. Much of the deterioration in performance was anticipated to come with the introduction of $NO_x$ requirements in 1973.

The Panel, in its 1972 visits to manufacturers, received reports on both the 1975 and 1976 emission control system progress. While manufacturers are still concerned with performance, particularly fuel consumption, the concern over vehicle driveability was diminished from the visits six to eight months earlier. There appear to be several reasons for this change:

1. The 1976 systems operate at richer carburetor settings than the 1975 systems discussed in the previous report. The engine is thus less sensitive to EGR.

2. Part of the reduction of $NO_x$ levels required between 1975 and 1976 would be achieved by the use of catalytic converters, which do not introduce any further acceleration or driveability problems.

3. 1972 models with EGR had been introduced in California with a tolerably low level of customer dissatisfaction. EGR was increased in 1973 models to meet the Federal $NO_x$ standard. It was felt that by 1976 enough experience with EGR would be available to overcome the severe driveability problems.

4. Further development with current carburetors had corrected some of the problems that had existed a year ago. Completely new carburetors will be introduced in 1975. These carburetors will be tailored to improve driveability by better design and new features. For example, it is anticipated that altitude compensation, which does not help meet the emission standards but does help with driveability, will be introduced.

5. Some improvements being introduced to give better emission control, such as electronic and higher energy ignition, more precise mixture ratio control (overall and to separate cylinders, more uniform EGR to all cylinders, etc.), also result in better driveability.

6. Small engine models (or options) will have been dropped because of unsatisfactory acceleration or driveability.

Thus, no substantial new acceleration or driveability problems are introduced with the 1976 emission control systems compared with the 1975 systems, though continued deterioration of these performance characteristics is expected. At the same time, considerable progress has been made in finding solutions to problems that appeared to be very serious one year ago. It seems likely that competitive pressures will result in further improvements and improved reliability in these performance areas. The effort required is essentially engineering development based on extensive field experience with these new systems.

The major long-term concern should be the steadily increasing fuel economy penalty resulting from the decreased compression ratio to allow the use of unleaded fuels, the use of EGR to control $NO_x$ emissions to very low levels, and the increasing engine sizes introduced to compensate for the loss in performance. The dual-catalyst system with its anticipated increase in EGR and its richer carburetor calibration relative to 1975 continues this trend. Previously, the Panel has reported estimates of increased fuel consumption of between 3 and 12 percent for 1975 prototype vehicles with conventional engines, engine modifications, and catalytic converters for HC and CO control, when compared with equivalent 1973 vehicles. The penalty for most manufacturers' 1975 vehicles now appears to be at the lower end of this range. However, 1976 dual-catalyst systems are estimated to show an additional increase of about 10 percent in fuel consumption above 1975 vehicles because of richer carburetor settings and increased amounts of EGR.

Of the alternative spark-ignition engines described in Chapters 7 and 8, preliminary data are available to evaluate the Toyo Kogyo Wankel engine with a thermal reactor in a compact car, and the Honda CVCC and Ford PROCO engines in compact and standard-size vehicles. All these alternatives promise better driveability than prototype 1975-76 emission-controlled conventional engines.

The Toyo Kogyo Wankel engine uses a fuel-rich carburetor calibration and a thermal reactor to achieve the 1975 standards. The driveability and acceleration characteristics of their 1975 prototype vehicles are good. The CVS fuel economy of these vehicles is about 5 percent less than that of an equivalent 1973 Wankel-powered Mazda (see Table 13); the 40 mph cruise fuel economy is about 8 percent less than the 1973 equivalent (23.5 mpg versus 25.6 mpg). Average CVS fuel economy for equivalent-weight 1973 reciprocating-engined vehicles is 18 mpg. Thus the 1973 Toyo Kogyo vehicle has a CVS fuel economy that is 30 percent less than the average vehicle in its weight class. The fuel economy of the Wankel engine can be improved by a leaner carburetor setting and by reducing seal leakage, however.

As EGR is used to further reduce $NO_x$ emissions with the Toyo Kogyo Wankel engine-thermal reactor combination, Figure 8 and Table 13 show that both fuel economy and driveability deteriorate.

The stratified-charge engines described in Chapter 8 exhibit better driveability and greater fuel economy than conventional engine 1975-76 prototypes. The acceleration capability is reduced, however, for the same engine displacement. The Ford PROCO system shows the best fuel economy of any spark-ignition engine system developed to meet the 1976 standards. Table 17 shows CVS fuel economy for a compact 2500-lb vehicle as between 20 and 25 mpg compared with an average of 19.9 mpg for 1973 vehicles in the 2500-lb inertia weight class. In standard-size cars, Table 17 shows the PROCO engine CVS fuel economy is 12.8 and 14.4 mpg for 4500-lb vehicles, which compares with an average of 10.1 mpg for 1973 conventional-engine 4500-lb vehicles. The Texaco TCCP system shows equivalent fuel economy to the PROCO engine in the military jeep (Table 16).

The Honda CVCC system for 1975 model-year shows good driveability, but slightly reduced acceleration and maximum torque compared with an equal-sized conventional engine. With a 140-CID Honda CVCC 1975 prototype engine replacing the 140-CID original in a GM 1972 Vega, the 1/4-mile acceleration times were increased by 4 percent and maximum torque decreased by 9 percent. The fuel economy was increased by 8 percent (CVCC 18.6 mpg versus original Vega 17.2 mpg for CVS test). The fuel economy of the 350-CID 1975 CVCC-engine 4500-lb vehicle given in Table 19, 11 mpg, is equivalent to the average fuel economy of 1970 4500-lb inertia weight vehicles.

As in other spark-ignition engines, as $NO_x$ emissions are reduced, the CVCC engine fuel economy decreases. With EGR to reduce $NO_x$ emissions below 0.4 g/mi, Table 21 shows that a Honda CIVIC 2000-lb vehicle suffers an 18 percent fuel consumption penalty relative to the 1975 CVCC system in the same ve[illegible]. Information on other performance characteristics of the 1976 CVCC engine is not yet available.

## 10. Averaging of Emissions

In evaluating the feasibility of meeting both the 1975 and 1976 standards, the issue of whether all emissions in certification fleet cars and production vehicles must be below the standards of 0.41 g/mi HC, 3.4 g/mi CO, and 0.4 g/mi $NO_x$, or whether only the average emissions from these vehicles must be below the standards is especially important. If averaging is not allowed during the certification procedure, which is the current practice, the manufacturer's confidence in the performance of his certification fleet needs to be greater. If averaging is not allowed in the testing of samples of production vehicles with the CVS test, then average emissions of production vehicles must be substantially below the standards.

The question of averaging of emissions from production vehicles was discussed in the CMVE Report of January 1, 1972. In that report it was concluded that since air quality is dependent on the average emissions from the vehicle population, only the average emissions of production vehicles need meet the standards over the vehicles' lifetimes. The importance of this issue is illustrated by the following figures:

Using emissions distribution curves obtained from current production vehicles, it has been estimated approximately that if 96 percent of the vehicles must meet the standards, the average emissions would have to be less than 0.6 times the standards; if 99.5 percent must be below the standards, average emissions would have to be less than 0.25 times the standards. Table 23 shows approximate low-mileage emission targets that would have to be reached before any control system could be considered promising. The assumption that the emissions distribution curve for 1976 type vehicles will have the same normalized spread as the curve for current production vehicles may well be optimistic.

## Table 23 Low-Mileage Emission Targets for Different Fraction of Production Cars Meeting Standards[a]

| Percent Cars Meeting Standard | Approx. Low-Mileage Emissions Targets, g/mi[b] HC | CO | $NO_x$ |
|---|---|---|---|
| Average | 0.18 | 1.5 | 0.18 |
| 96 | 0.11 | 0.12 | 0.11 |
| 99.5 | 0.045 | 0.38 | 0.045 |
| 1976 standards | 0.41 | 3.4 | 0.4 |

[a] Based on assumption that current emissions distribution when normalized will apply to 1976 emission control systems.

[b] 1975 CVS-CH emission test procedure: A factor of 2 deterioration over 50,000 miles and a 10 percent prototype to production slippage is allowed for.

It is obvious from the data presented in this report that low mileage emissions are far from these targets when almost all production vehicles must meet the standards. Thus, if averaging is not allowed, the prospects for meeting the 1975 and the 1976 standards are exceedingly remote. The current uncertainty over averaging of emissions as determined by the 1975 CVS-CH emissions test procedure should be resolved without further delay.

## APPENDIX A Organizations Consulted by the Panel

Between August 23, 1971, and November 30, 1972, members of the Panel visited, received material from, or heard presentations by the following organizations:

American Cyanimid
American Motors
Automobile Manufacturers' Association
Bendix Corporation
Robert Bosch
British Leyland Motors, Inc.
Chrysler Corporation
Curtiss-Wright Corporation
Daimler-Benz
Dresser Industries
duPont de Nemours & Co.
Engelhard Industries, Inc.
Environmental Protection Agency
Ethyl Corporation
Fiat
Ford Motor Company
General Motors
Gould, Inc.
W. R. Grace & Co.
Gulf Research and Development
Honda Motors, Ltd.
Humble Oil Company
International Harvester
Japan Catalytic Chemical Company
Johnson Matthey & Co., Ltd.
Monsanto Company
Nissan Motor Company, Ltd.
NSU
Oxy-Catalyst
Questor Automotive Products Company
Ricardo & Co., Ltd.
Texaco
Toyo Kogyo Co., Ltd.
Toyota Motor Co., Ltd.
U.S. Tank-Automotive Command
Universal Oil Products
Volkswagen

In addition, the Panel used data supplied by domestic and foreign automobile manufacturers who responded to the CMVE Questionnaires of September 27, 1971, and July 13, 1972.

## APPENDIX B - Questionnaires

## COMMITTEE ON MOTOR VEHICLE EMISSIONS

## QUESTIONNAIRE FOR FOREIGN AND DOMESTIC AUTOMOBILE MANUFACTURERS

### EMISSION CONTROL SYSTEMS

1. What engine-vehicle systems appear most promising for meeting the 1976 Federal emissions standards? What emission levels have been achieved with these systems?

2. For the systems described in answer to Question 1 above, what levels of durability, reliability, fuel economy, and driveability have been achieved?

3. What types of catalysts appear most promising for oxidation of HC and CO emissions? What levels of emissions control and durability have been achieved with these catalysts?

4. For the above catalysts, what are the major causes of loss in conversion efficiency with mileage accumulation?

5. Will sufficient quantities of the above oxidizing catalyst materials be available for use in a major portion of the 1975-76 vehicle population?

6. Which fuel and lubricant components appear to be most detrimental to the above catalysts? What are the apparent maximum permissible levels of these components in gasoline and/or lubricating oil?

7. What types of catalysts appear most promising for reduction of nitric oxide? What levels of emissions control and catalyst durability have been achieved with these materials?

8. What are the major causes of loss in conversion efficiency with mileage accumulation on the above catalysts?

9. Which fuel and lubricant components appear to be most detrimental to the above reducing catalysts? What are the apparent maximum permissible levels of these components in gasoline and/or lubricating oil?

10. Will sufficient quantities of the above catalyst materials be available for use in 1976 production automobiles?

11. What are the most recent developments related to control of HC and CO emissions during cold start operation?

12. What are the advantages and disadvantages of gasoline fuel injection relative to conventional carburetor-manifold systems, particularly as regards cold start emissions and driveability?

13. What is the current status of Wankel engine system development from the standpoint of exhaust emissions, fuel economy, reliability, durability, and driveability?

14. What level of Wankel engine production will be feasible for the 1976 model year?

15. What is the current stage of development of unconventional engines such as those employing stratified charge combustion, two-stage combustion, and high turbulence combustion processes? What emission levels, fuel economy, and driveability have been achieved?

16. At present how do catalytic converter systems compare with thermal reactor systems regarding emissions control, fuel economy, and durability? Does either system demonstrate a clear advantage for use with a particular class of car and/or power plant?

17. To what extent might fuel modifications be expected to improve emissions control system performance?

## CATALYSTS

1. Have you developed or tested catalysts that will successfully remove 90 percent of hydrocarbons and CO after a simulated endurance of 25,000 miles in laboratory testing? Repeat for 90 percent of $NO_x$. To achieve these results, give the range of temperature in which the catalyst must be maintained, maximum space velocity, gas composition, and maximum levels of lead, sulfur, phosphorous and ash. Provide your most recent data in support of your answer.

2. Have any of your oxidation and $NO_x$ catalysts been given a vehicle endurance test of 25,000 miles or longer? Provide data relative to these endurance tests. If the results

indicate that the emissions at the end of the test will not pass 1975-76 standards, discuss the external causes of the failure and the resulting damage to the catalysts, if known. Can you specify vehicle hardware or driving changes so that your catalysts will pass the test?

3. If catalyst replacement were to be allowed, what replacement schedule would enable your emission control system to satisfy the 1976 requirements? If one catalyst replacement were to be allowed in 50,000 miles, what interim standard could your control system satisfy?

4. What chemical elements are contained in your catalysts, and what is the maximum quantity required per automobile of 300 cubic inch displacement? What techniques can be used to recycle expensive elements in spent catalysts, and what is your estimate of recycle efficiency? These answers are needed to demonstrate that your catalysts will have adequate raw material supply, and that the catalyst debris will have been acceptable from toxicological consideration.